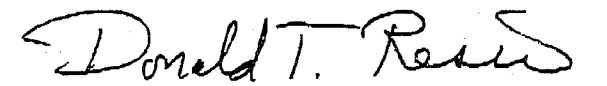
EXPERT REPORT

Prepared for United States Department of Justice
Robinson v. United States

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Preface

I was appointed to the position of Senior Technologist (ST) in May 1994. This position represents the highest technical rank in the DoD civil service, with fewer than forty such positions authorized within the Army. I have performed and directed engineering and oceanographic research for over thirty years. I serve as the technical leader for the Coastal Military Engineering program and am the Technical Manager (TM) for a new Advanced Technology Concept Demonstration (ACTD) for military logistics. I direct the MORPHOS project, which aims to improve the state of the art for predicting winds, waves, currents, surges, and coastal evolution caused by storms. Recently, I led the Interagency Performance Evaluation Taskforce (IPET) Task 5a (analysis of wave and surge effects, overtopping, and related forces on levees during Hurricane Katrina) and am now leading the Risk Analysis team for the South Louisiana Hurricane Protection Project. I earned my BA, MS, and PhD degrees at the University of Virginia, with the last of these awarded in 1974 in the field of Environmental Science: fluid dynamics.

The opinions expressed here are based upon a reasonable degree of scientific and engineering certainty. Because I have not had the benefit of Plaintiffs' final expert depositions, I reserve the right to amend my opinions regarding their work. Furthermore, I am prepared to address any additional issues within my areas of expertise that may arise at trial.

I have received no compensation for my work on this report and have not been deposed in the last four years. My publications in last 10 years are listed in Appendix A.

1. Introduction

The work described in this report was undertaken to estimate the run-up, setup, and overtopping effects of waves on levees along Reach 2 of the Mississippi River Gulf Outlet (Figure 1) for the six scenarios described in Table 1. The overall approach here is similar to that described in Volume IV of the IPET Report. A series of models and observations is used to develop detailed wave information. The ADCIRC model runs used here are described in Westerink (2008). These runs provide water surface elevations at half-hour intervals over the duration of Hurricane Katrina for each of the scenarios considered. The STWAVE model is exercised to estimate waves, using boundary conditions from the WAM model. Spectral models such as STWAVE and SWAN are not conventionally used to estimate run-up, overtopping, and setup on a levee since conventional spectral models only simulate processes within the mean water level and important aspects of run-up on levees occur above the mean water level. Consequently, wave information from the STWAVE model is used as a boundary condition for a fine-scale Boussinesq model. Such models have proven to be well suited for this type of wave modeling in many previous studies. In this study I use the same Cornell University Long and Intermediate Wave (COULWAVE) Model as was used in the IPET study, since that model and its application to this problem have been favorably reviewed by the National Research Council.

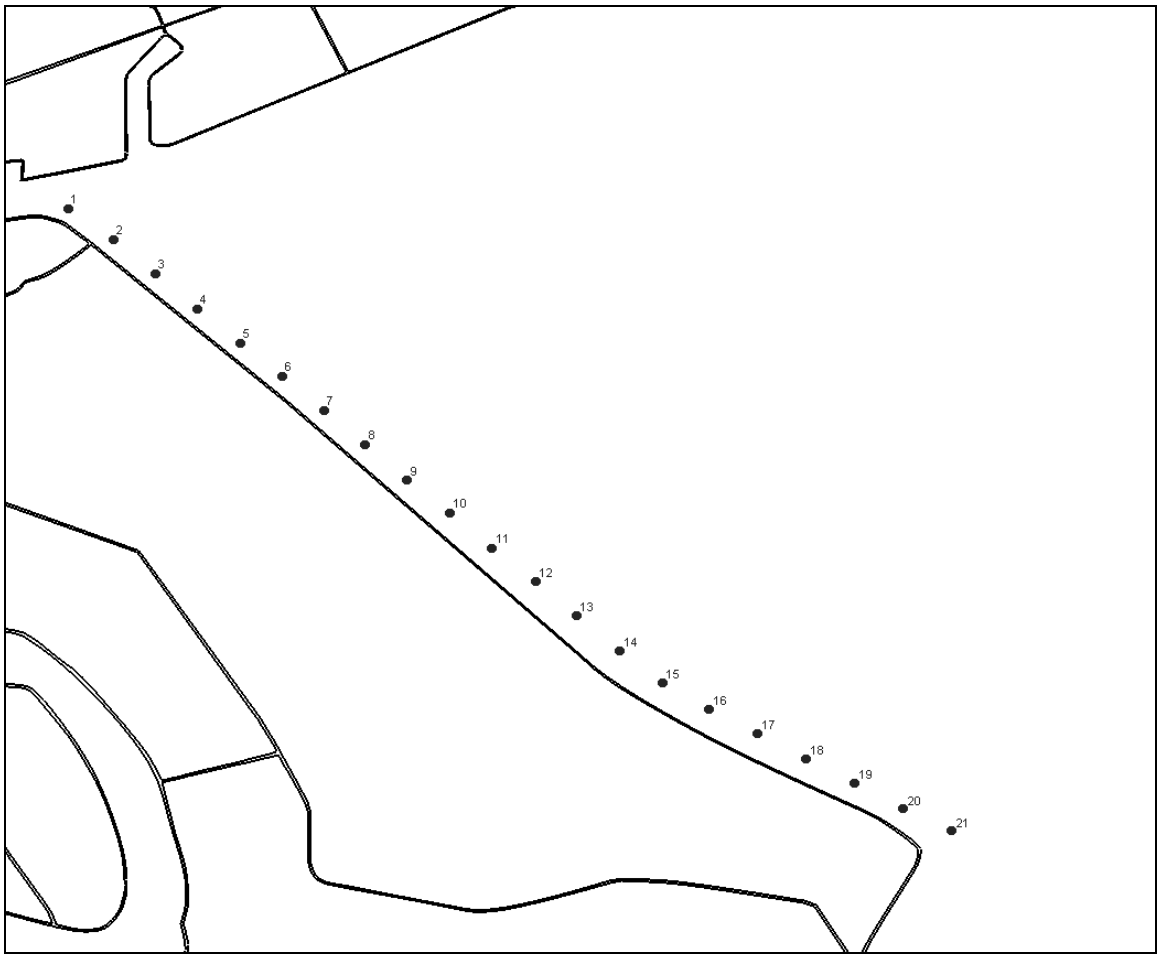


Figure 1. *Map showing locations of 21 points along MRGO Reach 2 for which wave information was generated to examine wave effects on levees for the six scenarios considered in this report.*

The COULWAVE model estimates velocities on the levees, wave setup, and overtopping rates for water passing over the levee crest. These estimates have been provided to the interior drainage group (Fitzgerald, 2008) and the levee erosion group (Ebersole, 2008) and used by them in their breach and flood modeling. The Boussinesq model converts information produced by the STWAVE model into information suitable for evaluating the relative differences in the scenarios described in Table 1. In this study, the characteristics of the levee and the terrain between the MRGO and toe of the levee remain constant for all six scenarios. Using a single generic levee and terrain profile in

the Boussinesq model ensures that the changes observed in these simulations result from the incident wave heights predicted by STWAVE and not from arbitrary or speculative changes in levee and terrain profiles.

In addition to modeling currents on the levee, wave setup and run-up, and overtopping, I have reviewed the corresponding reports produced by Plaintiffs' experts. My assessment of their analyses is detailed throughout this report.

1.1 Conclusions

My conclusions can be summarized as follows:

1. Waves and currents on the Reach 2 levee vary only slightly among the six modeled scenarios. I therefore conclude that the MRGO channel and the degradation of adjacent wetlands after 1956 had minimal effects on the waves and currents during Hurricane Katrina.

2. Wave overtopping is strongly affected by the freeboard between the surge level and the levee crest elevations. Pre-Katrina variations in levee crest elevations along Reach 2, measured by LiDAR, were in the order of several feet. This variation creates large differences in the overtopping rates at different locations along Reach 2. Significantly, the freeboard in many places was so large that the waves played only a very minor role in the overtopping flow. I therefore conclude that the principal causative factor in breach development was the character (especially crest elevation) of the LPV levee, not the wind-generated surge and waves.

3. Wave-generated velocities and overtopping rates are very similar at every location along Reach 2 for all scenarios except Scenario 4 ("No MRGO" with hypothetical 17.5 ft Lake Pontchartrain and Vicinity levee relocated to 40 Arpent

location). In every scenario (including Scenario 4), the velocities and overtopping rates at every location on the Reach 2 levee are far in excess of the rates necessary and sufficient to cause substantial levee degradation. I therefore conclude that the MRGO had a negligible effect on the wave-generated velocities and overtopping rates along the Reach 2 levee during Hurricane Katrina, and I further conclude that the degradation of the levee would have been substantially the same in any of the six modeled scenarios.

4. Although the Plaintiffs' Wave Report (Gautier et al., 2008) uses generally accepted models, its authors exaggerate the effect of the MRGO on wave heights along Reach 2 by making unwarranted assumptions and arbitrary choices, including specifically the following:

4.a Different friction formulations are used in the "Katrina Real Run" (Plaintiffs' Scenario 1) from those used in the hypothetical "No MRGO" scenarios (Plaintiffs' series 2 scenarios) and in the "MRGO as Designed" scenario (Plaintiffs' Scenario 3). The use of two sets of friction formulations creates a very substantial artificial difference between the "Katrina Real Run" scenario and the others. Because some of the difference in waves that is ascribed to the influence of the MRGO is instead attributable to the different friction formulations, the actual influence of the MRGO is not isolated.

4.b The vegetation charts used in the Plaintiffs' series 2 scenarios ("No MRGO") and their Scenario 3 ("MRGO as Designed") misrepresent the 1956 pre-MRGO vegetation in the "Golden Triangle" marsh east of Reach 2. The assumption of 80% wind-sheltering by this erroneously described vegetation significantly and erroneously reduces the modeled waves on the adjacent Reach 2

levee. Therefore, the estimates of the waves in Plaintiffs' Scenarios 2C and 3 are unreliable.

4.c The application of the van der Westhuysen et al. (2007) source terms to the MRGO—a short-fetch application of the type that van der Westhuysen specifically cautioned against—yields unrealistically high estimates of wave growth across the MRGO. The reported conclusions concerning the amplifying effect of the channel are unsound and unreliable.

5. The wave modeling methodology described in the report prepared by Robert G. Bea is unsuitable for estimating waves and their erosive effects on the Reach 2 levees under the conditions created by Hurricane Katrina. The most serious deficiencies in his wave modeling are the following.

5.a. The analysis of wave effects on a levee is flawed because wave effects are simulated for only a single levee elevation (17.5 ft) and a single time series of waves and surges. This methodology fails to analyze or describe the much different effects that occur where the levee crest is higher or lower, as was true of almost all of the Reach 2 levee before Hurricane Katrina. Before the hurricane, the levee had crest elevations ranging from less than 14 feet to more than 20 feet. Therefore, even apart from other flaws in Professor Bea's analysis, the wave effects would have been different from those that he describes in his report.

5.b The analysis of wave-generated velocities on a levee is not demonstrably reliable, because the use of LS-DYNA to model wave-generated velocities on a levee is an application of the software that has not been validated.

5.c The prediction of current velocities on the levee is unreliable because it is based on incorrect application of the LS-DYNA codes, including incorrect specification of the boundary conditions and the incorrect assumption that monochromatic waves can be used for representing wave run-up on levees in nature.

United States' Scenario	Plaintiffs' Scenario	MRGO Reach 1	MRGO Reach 2	LPVHPP Levee	Marsh	Description
1 "Katrina Real Run"	1	2005 pre-Katrina dimensions	2005 pre-Katrina dimensions	2005 pre-Katrina dimensions	2005 pre-Katrina conditions	Conditions at Hurricane Katrina landfall.
2 "No MRGO" (2005 wetlands)		1958 pre-MRGO (existing GIWW dimensions)	None (channel eliminated and topography raised to surrounding area)	2005 pre-Katrina dimensions	2005 pre-Katrina conditions	Conditions at Katrina landfall, if MRGO had not been constructed.
3 "No MRGO" (1956 wetlands)	2C	1958 pre-MRGO (existing GIWW dimensions)	None (channel eliminated and topography raised to surrounding area	2005 pre-Katrina dimensions	1956 pre-MRGO conditions	Conditions at Katrina landfall, if MRGO had not been constructed and marsh had remained in pre-MRGO condition.
4 "No MRGO" (1956 wetlands) (relocated LPV levee)	2A	1958 pre-MRGO (existing GIWW dimensions)	None (channel eliminated and topography raised to surrounding area)	Ideal levee (17.5 ft) at 40 Arpent location	1956 Pre-MRGO conditions	Conditions at Katrina landfall, if MRGO had not been constructed, marsh had been in 1956 pre-MRGO condition, and LPV levee had been constructed at 40 Arpent location.
5 "MRGO as Designed" (2005 wetlands)		Ideal MRGO (approximate design dimensions)	Ideal MRGO (approximate design dimensions)	2005 pre-Katrina dimensions	2005 Pre-Katrina conditions	Conditions at Katrina landfall, if MRGO had been at design dimensions.
6 "MRGO as Designed" (1956 wetlands)	3	Ideal MRGO (approximate design dimensions)	Ideal MRGO (approximate design dimensions)	2005 Pre-Katrina dimensions	1956 Pre-MRGO conditions	Conditions at Katrina landfall, if MRGO had been at design dimensions and marsh had been in 1956 pre-MRGO condition.

Table 1. *Description of six alternatives included in this report.*

2. Review of Plaintiffs' Wave Modeling for Prediction of Wave Impacts on Levees Along Reach 2 of the MRGO.

2.1 Review of Waves Methodology Used in Report Entitled "Wave Modeling New Orleans – Mississippi Gulf Outlet, Hurricane Katrina August 2005" (Final Report, July 9th, 2008) by Gautier, et al. (Herein termed the Plaintiffs' Wave Report)

In general, the Plaintiffs' Wave Report is technically sound and utilizes modeling technologies which are generally accepted for applications of the type described. It should be observed, however, that the report is not sufficiently definitive and, indeed, is problematic because of three key assumptions and choices that skew the analysis of waves in Plaintiffs series 2 scenarios ("No MRGO") and their Scenario 3 ("MRGO as Designed"). These three assumptions/choices allowed the modelers to vastly overstate the differences between the estimated waves in Scenario 1 ("Katrina Real Run") and those in Scenarios 2C and 3.

A. Plaintiffs' Wave Report dubiously assumes that a segment of the Reach 2 levee would have been shielded from hurricane winds by cypress trees if the MRGO had not been constructed.

The first problematic assumption in Plaintiffs' Wave Report is its speculative and insupportable assumption that cypress trees would have existed in the "Golden Triangle" east of the LPV Reach 2 levee in 2005 if the MRGO had not been constructed. The figure on page 22 of the Plaintiffs' Wave Report reflects this assumption of cypress coverage, but the figure is not referenced. It appears to be drawn from a 1930s Cypress Tree Map instead of the 1950 habitat data available from just before MRGO construction. *Compare* FitzGerald et al. 2008, Fig. 4.2 (1950s Cypress Tree Map) *with* FitzGerald et al. 2008, Fig. 4.8 (1930s Cypress Tree Map). The vegetation pattern that is used to model waves in Plaintiffs' series 2 scenarios ("No MRGO") and Series 3 ("MRGO as

Designed") is supposed to replicate wetlands conditions that existed immediately prior to the construction of the MRGO, on the dubious assumption that the wetlands would have remained static for half a century if the MRGO had not been constructed. But rather than modeling vegetative conditions depicted in Plaintiffs' 1950s habitat map the pattern applied in Plaintiffs' series 2 scenarios and in Plaintiffs' Scenario 3 appears to have been drawn from a 1930s land use map.

The application of a vegetation pattern that no longer existed when the MRGO began to be constructed is significant. Most significantly, the 1930s map depicts scattered Cypress trees in the "Golden Triangle" east of the eventual location of the MRGO. The 1950s map does not. The subjective (and apparently erroneous) estimation of vegetation patterns in Plaintiffs' Scenarios 2C and 3 significantly skews Plaintiffs' modeling of waves on the segment of the Reach 2 levee that is nearest the trees shown in the "Golden Triangle" on the 1930s map. Consequently, the reported conclusions as to the effects of the MRGO on waves in this area are unsound. The conclusions are based on a comparison of waves that are erroneously assumed to be 80% sheltered from winds in Plaintiffs' Scenarios 2C and 3 with waves that are assumed not to have been sheltered in Plaintiffs' Scenario 1, the base case, which has a different vegetation pattern, one which is assumed to approximate the actual pre-Katrina 2005 wetlands configuration.

Even if it were to be assumed that the vegetative pattern applied in Plaintiffs' Scenario 2C and 3 accurately depicted the location of cypress trees in the 1950s, the assumed frictional effect of that vegetative pattern is problematic. The table on page 22 of the Plaintiffs' Wave Report assigns a vegetation height of 2 m for the marsh vegetation. Spartina is typically not taller than 1 m, however, and Cypress trees usually

have a height of approximately 5 m. I am not aware of any peer-reviewed journal papers which establish or validate a friction coefficient for waves passing through these types of vegetation. Assigning a height of 2 m, as is done in the report, leads me to conclude that the wave estimates resulting from the use of this assigned height are not demonstrably reliable.

The Plaintiffs' Wave report also assumes that in areas with cypress forest, the winds are reduced by 80 percent. This assumption of extreme wind reduction exacerbates the effects of the misplaced cypress forest, creating artificially low waves in the "No MRGO" and "MRGO as Designed" scenarios. As Figure 4.1 of the Plaintiffs' Wave Report shows, even in areas where marsh vegetation (as opposed to forested swamp) dissipates wave energy, strong winds continue to pump energy into the wave field (up to steepness limited heights). Thus, the winds largely make up for the frictional dissipation of marsh that is not sheltered by forest. In contrast, where winds are blocked by a forest canopy, the dissipation is pronounced. I therefore conclude that the improper application of wind sheltering in the Plaintiffs' Wave Report resulting from the mischaracterization of the pre-MRGO vegetation plays a substantial role in producing the differences in wave heights between the "Katrina Real Run" scenario, on the one hand, and the "No MRGO" and "MRGO as Designed" scenarios, on the other. The use of the 1930s vegetation pattern instead of the 1950s pattern results in an artificial overstatement of the effect of MRGO on waves. This mischaracterization of pre-MRGO vegetation prevents Plaintiffs' counterfactual scenarios ("No MRGO" and "MRGO as Designed") from isolating the influence of the MRGO on waves and velocities at the Reach 2 levee.

B. Plaintiffs' Wave Report arbitrarily applies incompatible bottom friction formulae, using one set of formulations to activate bottom friction in the "Katrina Real Run" base case and a second set to activate bottom friction in the "No MRGO" and "MRGO as Designed" scenarios.

The second key problem is that Plaintiffs' Wave Report uses one set of bottom friction formulations in modeling Scenario 1 ("Katrina Real Run") and another set to model all of the other scenarios. The study applies the JONSWAP formulation to activate bottom friction (effecting wave dissipation) in Scenario 1 ("Katrina Real Run"). In contrast, it applies the Collins bottom friction formulation, with coefficient values of 0.49, 0.98, and 2.0 in vegetated areas in the "No MRGO" and "MRGO as Designed" scenarios. *See* Plt. Wave Report 12. Direct comparisons of the wetlands effect in the "Katrina Real Run" scenario with wetlands effect in the "No MRGO" and the "MRGO as Designed" scenarios are therefore not possible, because different friction formulations are applied. Vegetation density and coverage do vary in the area of study, and the constant JONSWAP values (appropriate for sand bed but not vegetation) are therefore inappropriate for the "Katrina Real Run" base case scenario. This inappropriate application of JONSWAP values artificially suppresses the dissipating effects of vegetation and unrealistically increases the estimates of wave heights in the "Katrina Real Run" scenario. The different treatments of vegetative friction coefficients are is critical to the report's conclusion that frictional effects would be much more dominant in this area if the MRGO had not been constructed. In my opinion, this conclusion is unsound because it flows not only from the assumed change in conditions but also from the use of different friction formulations.

The JONSWAP friction coefficient values applied in the "Katrina Real Run" base casecase range from C_b=0.038 (large coverage grid) to 0.067 m^2/sec^3 (smaller coverage

grids). The equivalent coefficient using the Collins formulation would $C_b=C_fgU_{rms}$, where C_f is the Collins coefficient. In the "No N MRGO" and "MRGO as Designed" scenariosss, however, Collins friction coefficient values of C_f = 0.015, 0.49, 0.98, and 2.0 are used for open water, marsh, dense marsh, and cypress tress. For peak wave conditions in the MRGO area, the wave height is approximately 2.5 m with a peak spectral period of 6 sec in a depth of 4.5 m, which generates bottom velocities around 1.5 m/sec. Using these values, the bottom friction coefficients applied in the "No MRGO" and "MRGO as Designed" scenarios are 0.22, 7.2, 14, and 29 m^2/sec^3, which are factors of 100 to 400 times greater than the values applied in the "Katrina Real Run" base case.

The Collins friction coefficients are based on an equation given on page 18 of the Plaintiffs' Wave Report and referenced a poster in Appendix B of that report. Although it could be expected expected that friction factors would be a function of vegetation rigidity, diameter, spacing, and stem height, this simple formulation is not well documented or validated. I could not find a peer-review article to support the poster, and the poster supplies no detail on the range of parameters applied in the study. The report provides only one validation plot—a plot that includes error as large as as50 percent. .Other studies have been unable to verify the dependence of attenuation on plant density, height, and species (Fonseca and Cahalan 1992, Knutson et al. 1982). Consequently, this poster and the frictional values applied in Plaintiffs' Wave Study appear to be arbitrary and not demonstrably correct.

C. Plaintiffs' Wave Report applies a wave growth source term that overestimates wave growth on short fetches like the MRGO fetch, making the reported conclusions as to the effect of the MRGO on waves suspect.

The third key problem with the Plaintiffs' Wave Report is that it uses a wave growth source term in SWAN that is known to overestimate wave growth on short fetches. This is the very type of application used by the Plaintiffs in their report for estimating wave growth resulting in Hurricane Katrina when hurricane winds blew normally across the MRGO (*i.e.,* at right angles to the channel). The SWAN model reportedly is applied in the plaintiffs' study using the source term option "WESTH," based on Westhuysen et al. 2007, instead of the default generation term that is usually applied. This is a misapplication of the WESTH source term. The reference article in which the WESTH source terms are described warns that the term "significantly overestimate[s]" wave characteristics when applied to short fetches: "[T]he investigated and default models generally perform equally well in predicting significant wave height yielding small biases and high correlations. **An exception to these encouraging results is found over very short dimensionless fetches, such as for station FL25, under SW wind, where the total spectral energy is significantly overestimated**" (emphasis added).

This same overprediction is seen in the Plaintiffs' Wave Report estimations of wave growth across the MRGO in the "Katrina Real Run" base case. Wave heights reportedly increase 2-3 ft across the MRGO, a fetch of about 1000-1500 ft. The default version of SWAN does not give this growth (nor does STWAVE) but instead produces much smaller increases in wave growth—increases of a few tenths of a foot. Since the application of the WESTH source terms to short fetches has been recognized to

overestimate wave growth, the application of it in Plaintiffs' Wave Report is clearly inappropriate and produces demonstrably unreliable estimates of the influence of the MRGO.

Figures 2 to 7 show SWAN outputs for Scenario S1 (Katrina with existing conditions) on the fine grid (20-m spacing) for SWAN with the default wave generation and the van der Westhuysen et al. (2007) source term (option GEN3 WESTH). The results are shown along six transects that cross the MRGO. See Figure 2.2 in the Plaintiffs' Wave Report (2008) for the transect locations. From the above discussion, it should be noted that this is expected and that the "Default" source terms should be used in this situation.

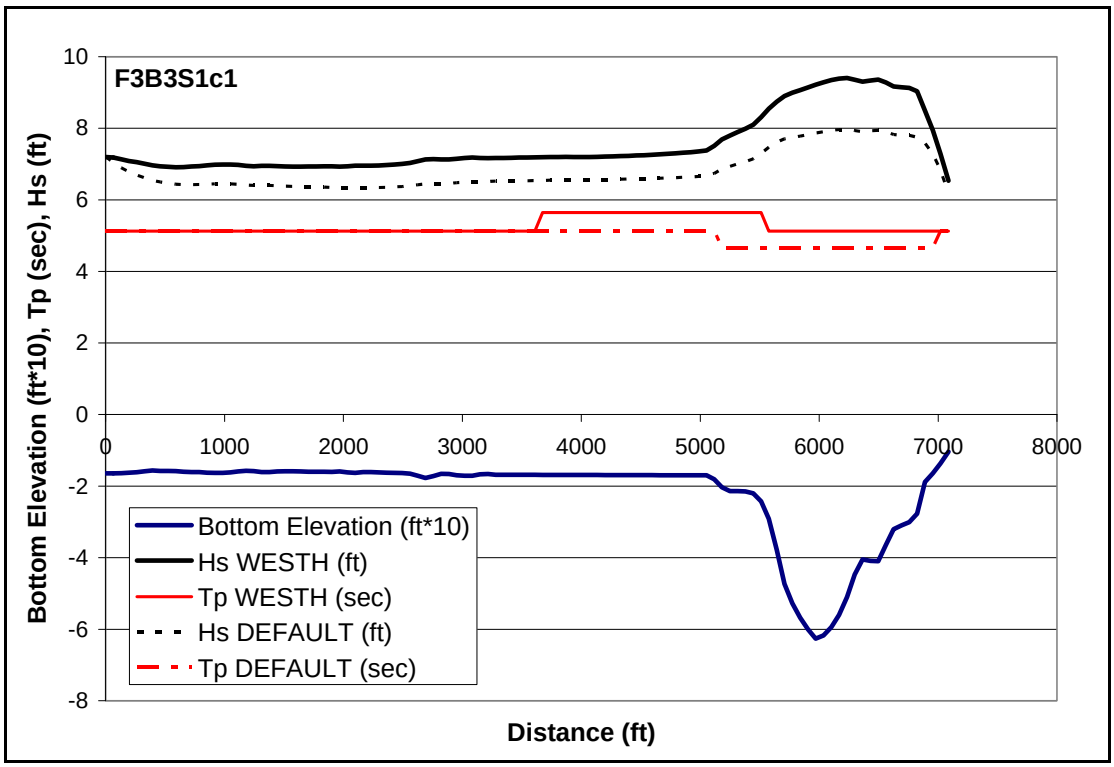


Figure 2.Comparison of wave heights and periods using WESTH source terms in SWAN compared to those obtained with the default source terms for Transect 1.

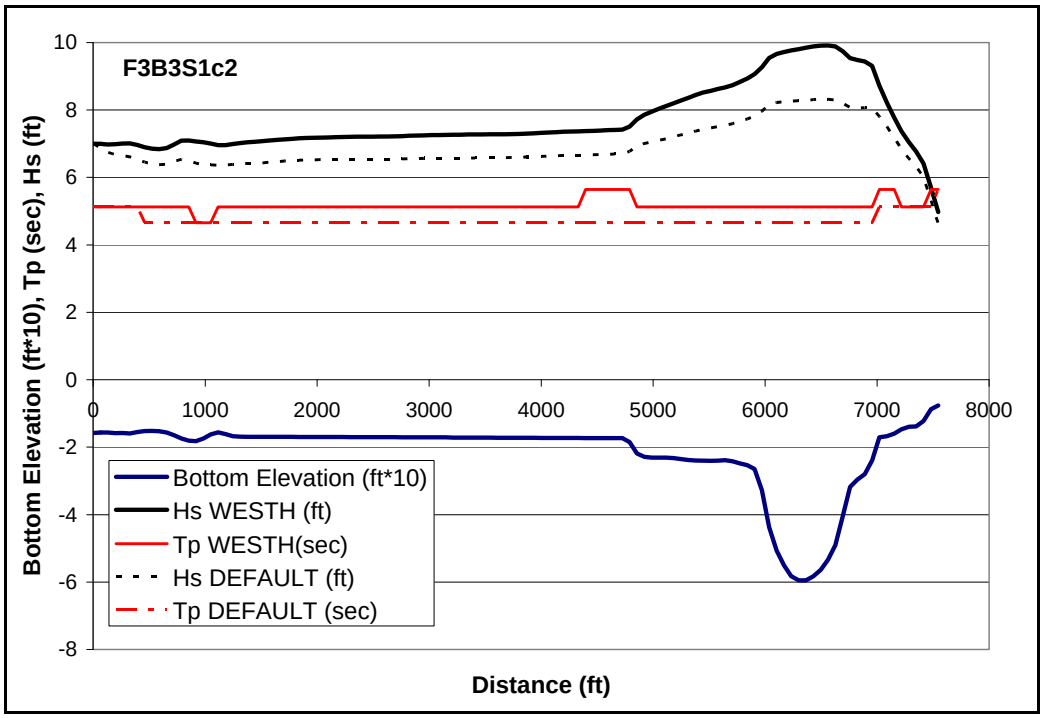


Figure 3. .Comparison of wave heights and periods using WESTH source terms in SWAN compared to those obtained with the default source terms for Transect 2.

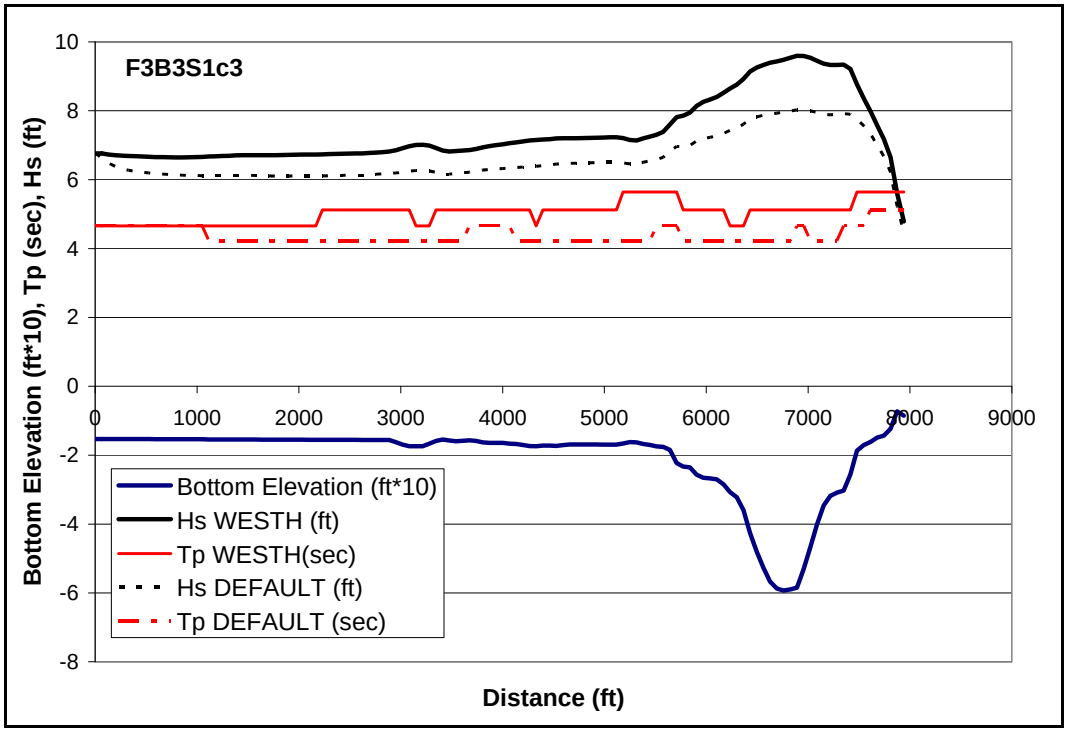


Figure 4. .Comparison of wave heights and periods using WESTH source terms in SWAN compared to those obtained with the default source terms for Transect 3.

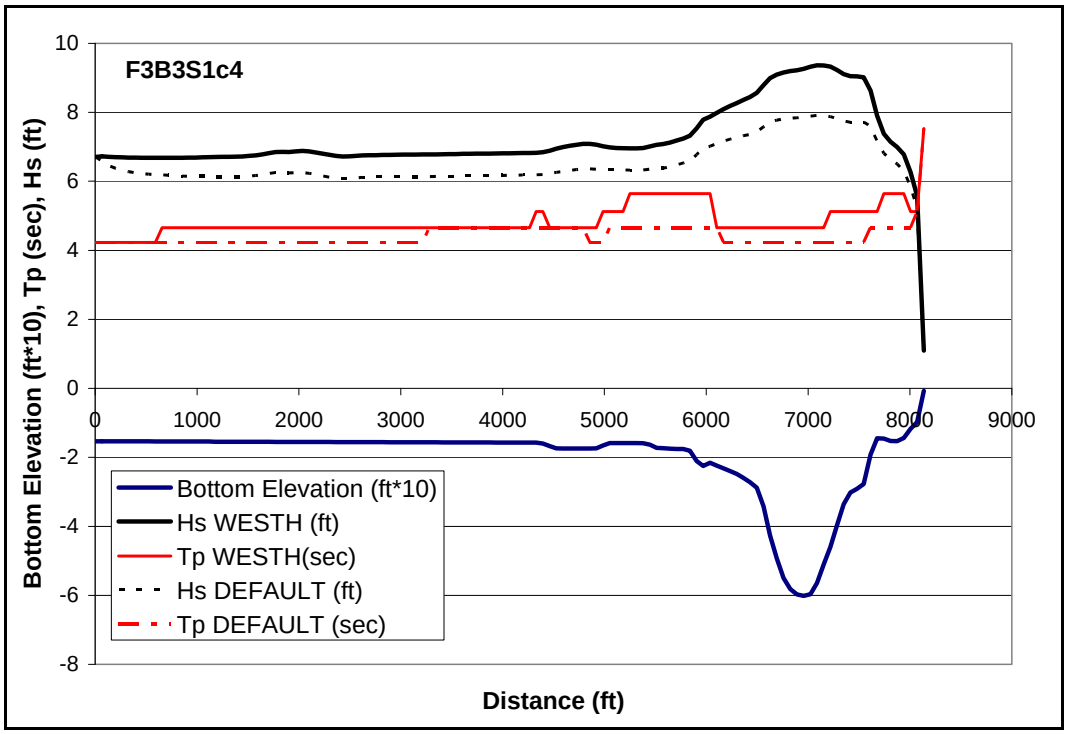


Figure 5. .Comparison of wave heights and periods using WESTH source terms in SWAN compared to those obtained with the default source terms for Transect 4.

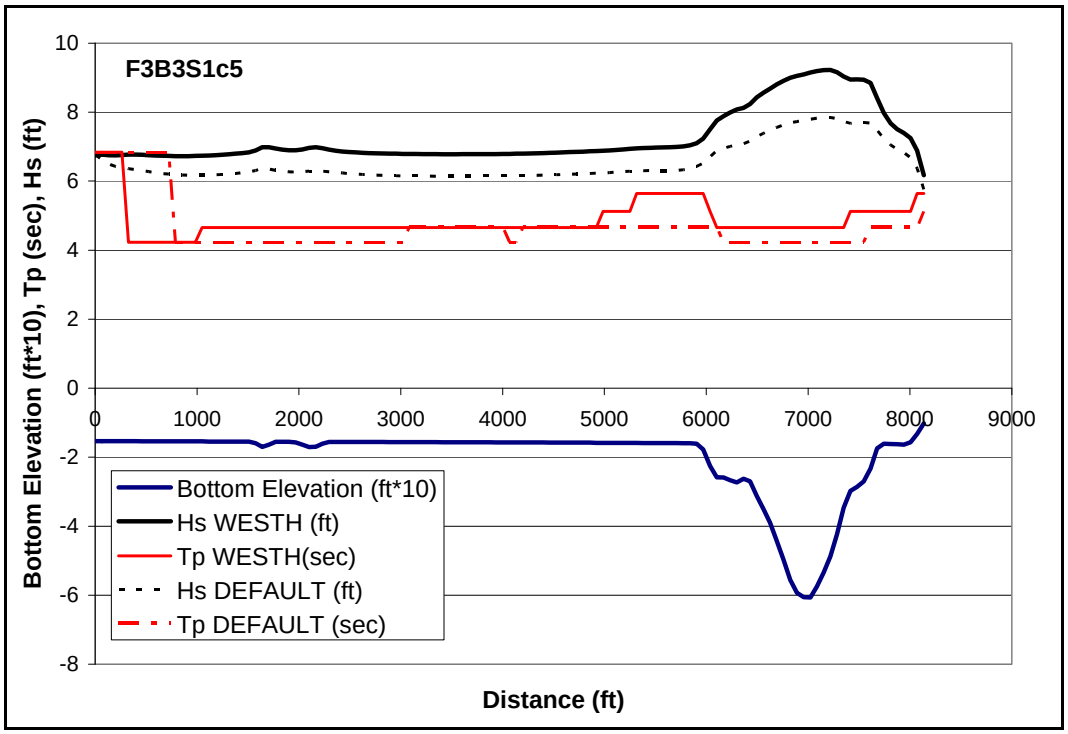


Figure 6. .Comparison of wave heights and periods using WESTH source term sin SWAN compared to those obtained with the default source terms for Transect 5.

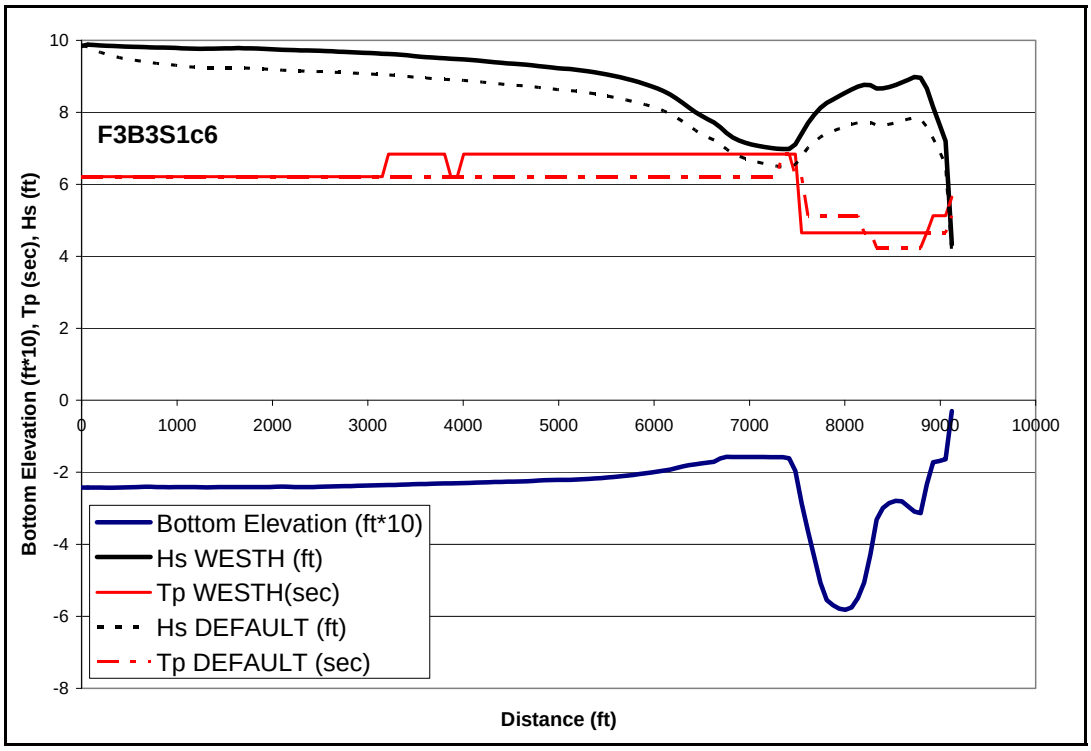


Figure 7. .Comparison of wave heights and periods using WESTH source term sin SWAN compared to those obtained with the default source terms for Transect 6.

2.2 Review of Waves Methodology Used by Professor Bea in Technical Report 1

In this section of my report, I critique the approach used by Professor Bea in his report entitled Technical Report 1, which was included in a set of documents that I received in July 2008. The stated purpose of that report was "to evaluate the magnitude of earthen berm/spoil bank (EBSB) erosion resulting from wave-induced scour on the flood side of the Mississippi River Gulf Outlet (MRGO) EBSB during Hurricane Katrina in August 2005." However, in my opinion, there are several serious deficiencies in the wave methodology used by Professor Bea which preclude the use of his wave information for such a purpose:

1. Simulation of wave effects for only a single levee elevation (17.5 ft) and a single time series of waves and surges.

2. Lack of demonstrated applicability of the LS-DYNA model for Professor Bea's analysis of wave-generated velocities on a levee.

3. Incorrect application of the LS-DYNA code for predicting velocities on a levee.

Each of these three shortfalls, will be discussed in the following sections:

1. Simulation of wave effects for only a single levee elevation (17.5 ft) and a single time series of waves and surges.

Professor Bea's conclusions are based on the premise that levees, waves, and surges at other locations along Reach 2 would have erosive tendencies which are essentially identical to the scenario that he chose to simulate. Given the acute sensitivity of wave velocities and overtopping to the relative freeboard (the difference between the elevations of the mean water level and the levee crest) that will be shown subsequently in this report, overtopping rates and wave-generated velocities relating to potential levee erosion undoubtedly varied substantially along Reach 2 during Hurricane Katrina. In fact, our estimates indicate that during Katrina overtopping rates and wave-generated velocities varied from essentially zero at some of the higher levee sections to extremely high values at some of the lower levee sections. The use of a single scenario of levee elevations, surges, and wave conditions neglects this natural variation along Reach 2 and creates an unrealistic, artificial threshold for the occurrence/non-occurrence of erosion.

2. Lack of demonstrated applicability of the LS-DYNA model for Professor Bea's analysis of wave-generated velocities on a levee.

As stated in the LS-DYNA Theory Manual, "LS-DYNA is a general purpose finite element code for analyzing the large deformation static and dynamic response of

structures including structures coupled to fluids." It is, however, not a code that has been specifically validated for wave propagation/transformation in near-coast environments. In particular, there are unresolved scales of motion within both bottom friction and wave breaking which are critical to these processes. For example: turbulent interactions with the bottom and vegetation and instabilities/turbulence within the wave crests are not resolved by the LS-DYNA grid that is used. Accepted treatment of such effects remains empirical and requires extensive inter-comparisons with laboratory and field data to develop and validate approximations within a model before such a model can be considered appropriate for the purpose for which Professor Bea uses the LS-DYNA code.

To my knowledge, not a single peer-reviewed journal article has been published demonstrating the accuracy of the LS-DYNA code for the type of application that is used by Professor Bea. It is common practice to provide at least a small list of references demonstrating the applicability of a tool for a given purpose in engineering reports, so the lack of such references in Professor Bea's report suggests that such references indeed do not exist. The obvious difficulty in using the LS-DYNA code (for example Professor Bea was forced to reduce the 258-foot span between the MRGO an the toe of the levee to 50 feet "to reduce the numerical computation time" makes it all the more surprising that he did not use one of the many excellent wave models which are available for predictions of nearshore waves on slopes, such as the COULWAVE model used in this report. Boussinesq models such as COULWAVE have been thoroughly validated in many publications (See for example the partial list of peer-reviewed publications included in Appendix B of this report). Considerable effort has gone into ensuring that energy losses due to wave breaking and bottom friction are accurately represented within these models.

A corresponding level of effort appears to be totally lacking for the LS-DYNA model. Consequently, the LS-DYNA model cannot be considered an accepted engineering tool for application to nearshore wave predictions.

3. Incorrect application of the LS-DYNA code for predicting velocities on a levee.

Methods adopted in Professor Bea's analysis are inconsistent with our current understanding of the physics/hydrodynamics of nearshore waves. These inconsistencies include: 1) the use of monochromatic waves rather than irregular waves in his simulations, 2) using an incorrect boundary condition to generate waves entering the computational domain and 3) suppression of natural variability in wave-generated velocities due to use of monochromatic waves in simulations.

It has been widely established in the literature that monochromatic waves do not produce the same results for run up and wave heights incident on a slope. As an example of this, Figure 8 shows the results from the validation of COULWAVE against laboratory data for the case of regular waves. As can be seen here, regular (monochromatic) waves tend to all peak at the same point along the slope with the wave heights at this point being substantially larger than the incident wave height. On the other hand, Figure 9 shows the results for a similar comparison of wave transformations predicted by COULWAVE to laboratory waves for the case of irregular (spectral) waves in a basin for a comparable value of ka (wave steepness) as can be associated with the waves conditions at 0730 in Professor Bea's analysis (wave period equal to 5.5 seconds and wave height equal to 6.1 feet). As can be seen in this figure, wave heights propagating along the slope do not become larger than the incident wave heights. This is due to the fact that the combination

of all the spectral components produces waves which break at different locations along the length of the basin. Waves in hurricanes are clearly not monochromatic and should be treated with models that use irregular (not monochromatic) boundary conditions. Professor Bea's analysis is extremely deficient in its assumption of monochromatic waves for this analysis, since such waves do not behave in a fashion that is consistent with the natural waves in hurricanes.

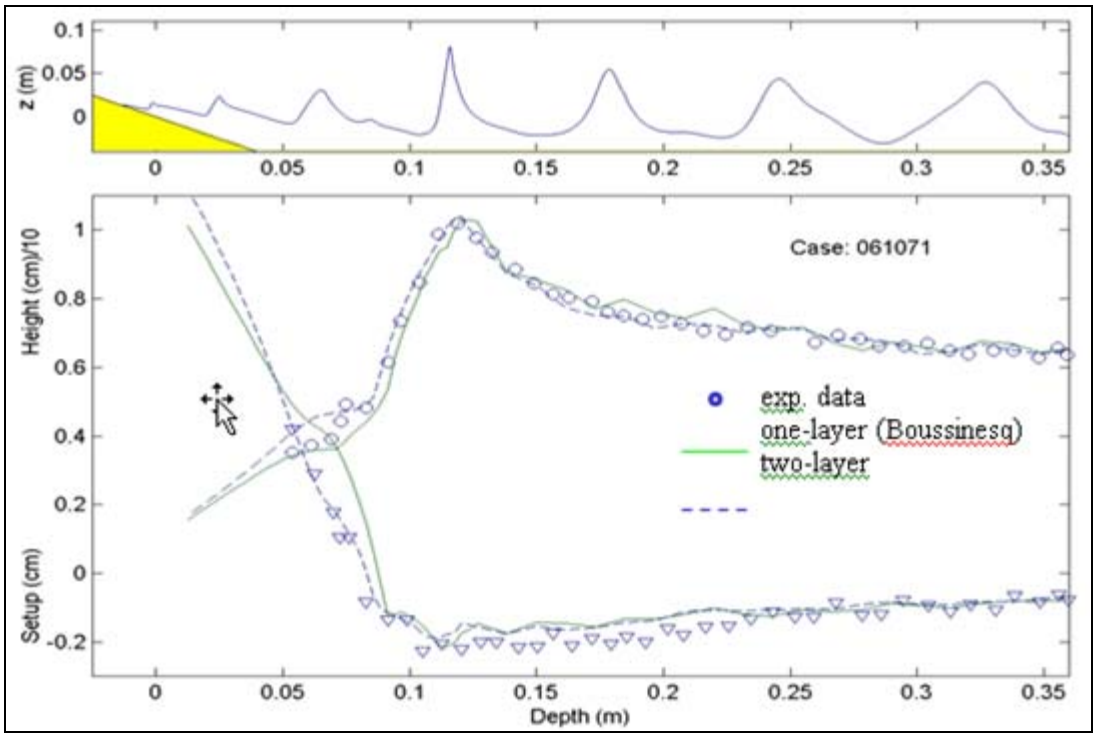


Figure 8. Comparison of COULWAVE result to experimental laboratory data for monochromatic waves. Note the substantial amplification of the waves in the depth range 0.11-0.14 created by wave shoaling prior to significant breaking on the slope.

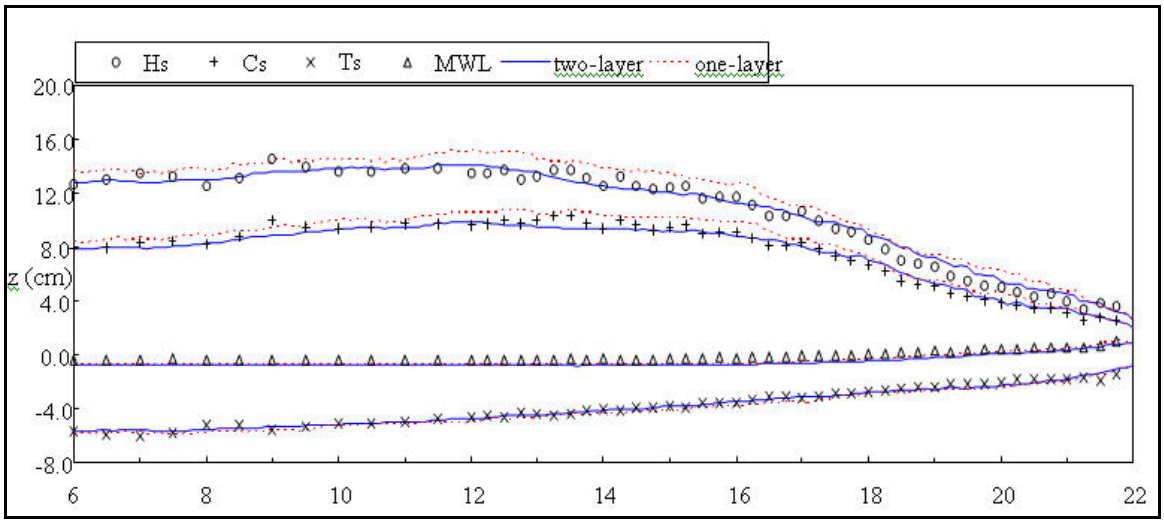


Figure 9. Predictions of COULWAVE compared to experimental laboratory data for spectral (irregular) waves for incident waves with dimensionless amplitude (ka) equal to 0.114. Note that the region of substantial amplification of the waves does not occur in this case since signification wave breaking occurs before shoaling can amplify these waves.

A second major problem with Professor Bea's analysis can be found in his treatment of the boundary conditions that LS-DYNA runs. He lists the "wave generation equations" on page 67 of his report as:

$$u = v\sin(\omega t) + overtopping_velocity$$

$$w = v\cos(\omega t)$$

where:

u = horizontal velocity component of the wave;

1. w = vertical velocity component of the wave;

v is a scalar constant with dimensions of length/time;

ω is the radial frequency of the incident wave;

t is time; and

$overtopping_velocity$.

The problem with this boundary formulation is that it is not consistent with water waves in any depth. The general form for wave velocities in arbitrary depth is given by

2.

$$u(z) = \omega a \frac{\cosh([k(d+z)]}{\sinh[kd]} \sin(\omega t)$$

$$w(z) = \omega a \frac{\sinh([k(d+z)]}{\sinh[kd]} \cos(\omega t)$$

where:

a is the amplitude of the wave;

d is water depth; and

z is the vertical location above the bottom boundary within the wave.

The important distinction made here is twofold. First, in no depth does equation 2 reduce to equation 1, so Professor Bea's specification of velocities at the boundary is simply wrong. Second, no dependence on depth is seen in either the vertical or horizontal velocities in Professor Bea's boundary conditions, whereas there is such a dependency in equation 2. Because of this dependency in equation 2 the particle paths change form from the surface (where they follow the wave profile) to increasing eccentricity at the bottom (where they become straight lines moving parallel to the bottom – so w should essentially be equal to zero at the bottom since water cannot move through the bottom), but in equation 1 they keep the same values throughout the water column. Thus, the velocity vectors of a wave over a fixed bottom should become parallel to the bottom as the bottom is approached. In Figure 10 (Figure 53 from Bea's Technical Report 1), it appears that the angle and magnitude of the velocity vectors along the vertical "paddle" used to generate the waves do not vary much as the bottom is approached and the velocity vectors in the interior of the fluid in the vicinity of the paddle do not appear to vary in a fashion consistent with equation 2 but are consistent with equation 1 which is

incorrect. If the boundary conditions are incorrectly specified in a numerical model, the results obtained in the interior of the fluid are inconsistent with appropriate wave theory and cannot provide correct estimates of near-bottom velocities.

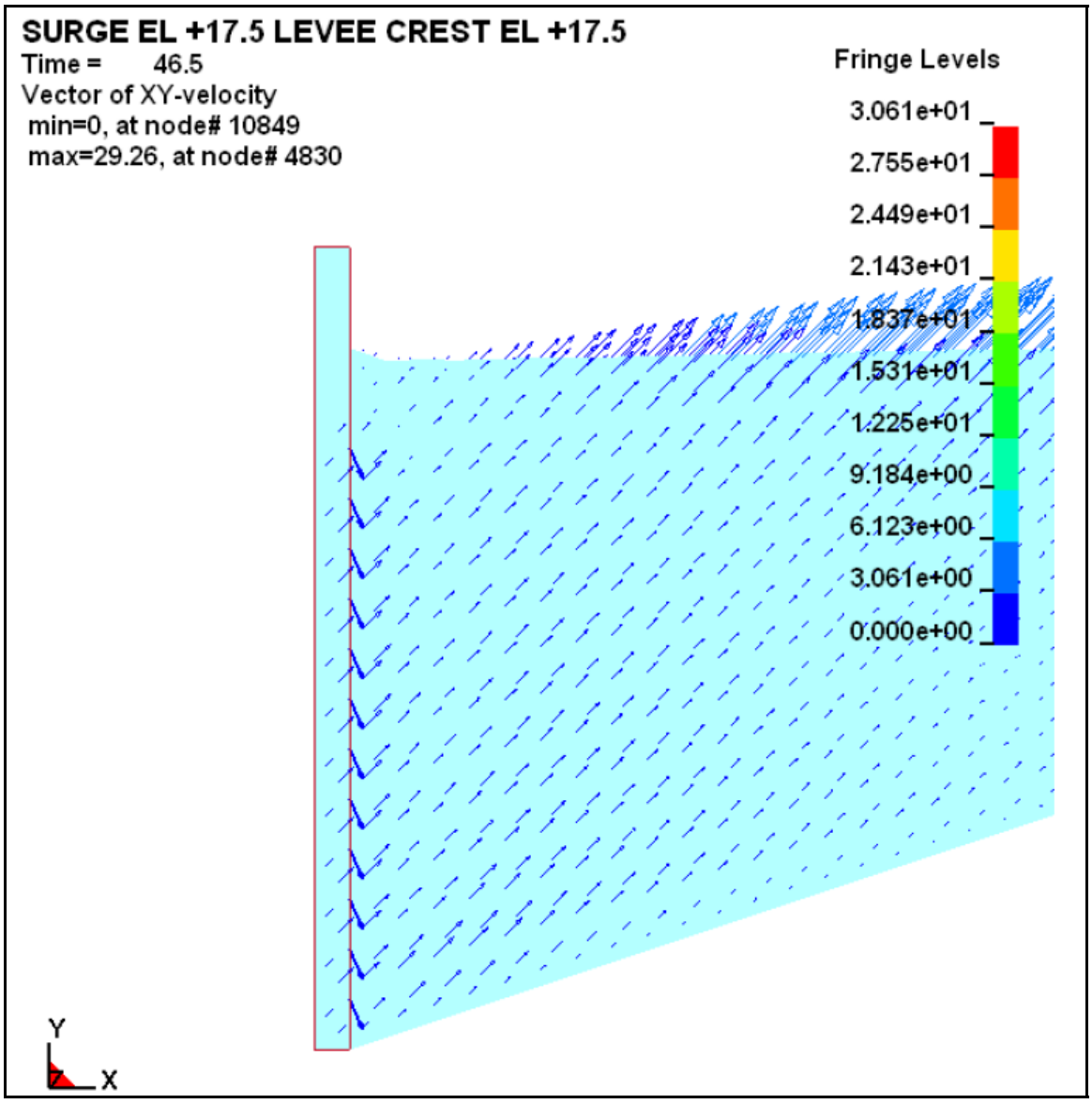


Figure 10. This figure is the lower left hand panel in Professor Bea's Figure 53. It shows velocity vectors within the fluid in LS-DYNA that do not appear consistent with the appropriate wave theory for the relative depth of the monochromatic waves used by Professor Bea in his simulations.

Finally, Professor Bea's use of monochromatic waves in his simulations suppresses the very large natural variability in wave-generated currents related to the irregularity of wind-generated waves in nature. In Professor Bea's simulations each incident wave is specified at the boundary as exactly identical to the preceding wave. The appearance of some irregularity in Professor Bea's time series is due only to the interactions between partial reflections from the levee and his incoming wave boundary. This is not equivalent to what happens in nature where waves vary very substantially from one wave to the next. Thus, the velocities generated by Professor Bea do not properly represent the waves that occur in nature.

3. Specification of Waves Along Reach 2 of MRGO

3.1 Overview of Effort

This section is a description of the series of wave models utilized to produce estimates of wave overtopping and velocities at the Reach 2 levee. First, the application of the STWAVE model using boundary conditions taken from the WAM model will be described and then the application of the COULWAVE model will be described using the outputs from the STWAVE model as its boundary conditions. After the modeling methodology is explained, results from these runs for the six scenarios listed in Table 1 will be given and discussed.

3.2 Application of STWAVE to produce waves in the MRGO

The numerical model STWAVE (Smith 2000; Smith, Sherlock, and Resio 2001; Smith and Smith 2001; Thompson, Smith, and Miller 2004; Smith 2007) was used to

generate and transform waves to the shore for Hurricane Katrina. STWAVE numerically solves the steady-state conservation of spectral action balance along backward-traced wave rays:

$$(C_{ga})_x \frac{\partial}{\partial x} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} + (C_{ga})_y \frac{\partial}{\partial y} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} = \sum \frac{S}{\omega_r} \qquad (1)$$

where

C_{ga} = absolute wave group celerity

x,y = spatial coordinates, subscripts indicate x and y components

C_a = absolute wave celerity

μ = current direction

α = propagation direction of spectral component

E = spectral energy density

f = frequency of spectral component

ω_r = relative angular frequency (frequency relative to the current)

S = energy source/sink terms

The source terms include wind input, nonlinear wave-wave interactions, dissipation within the wave field, and surf-zone breaking. The terms on the left-hand side of Equation 1 represent wave propagation (refraction and shoaling), and the source terms on the right-hand side of the equation represent energy growth and decay in the spectrum.

The assumptions made in STWAVE are as follows:

a. Mild bottom slope and negligible wave reflection.

b. Steady waves, currents, and winds.

c. Linear refraction and shoaling.

d. Depth-uniform current.

STWAVE can be implemented as either a half-plane model, meaning that only waves propagating toward the coast are represented, or a full-plane model, allowing generation and propagation in all directions. Wave breaking in the surf zone limits the maximum wave height based on the local water depth and wave steepness:

$$H_{mo_{\max}} = 0.1L \tanh kd$$

where

H_{mo}= zero-moment wave height

L = wavelength

k = wave number

d = water depth

STWAVE is a finite-difference model and calculates wave spectra on a rectangular grid. The model outputs zero-moment wave height, peak or mean wave period, and mean wave direction at all grid points and two-dimensional spectra at selected grid points. For these applications, spatially variable surge and wind fields were applied.

A. Wave Model Inputs

The inputs required to execute STWAVE include:

a. Bathymetry grid (including shoreline position and grid size and resolution).

b. Incident frequency-direction wave spectra on the offshore grid boundary.

c. Current field (optional).

d. Surge and/or tide fields, wind speed, and wind direction (optional).

e. Bottom friction coefficients (optional).

B. Wave Model Outputs

The outputs generated by STWAVE include:

a. Fields of energy-based, zero-moment wave height, peak spectral wave period, and mean direction.

b. Wave spectra at selected locations.

c. Fields of radiation stress gradients to use as input to ADCIRC (to calculate wave setup).

STWAVE was applied in a half-plane mode on three grids for the southern Louisiana area: Louisiana Southeast, Louisiana South, and Mississippi/Alabama (Figure 11). Three grids were used to take advantage of the efficient half-plane version of STWAVE for the three outer grids (which must approximately align with the shoreline) and to concentrate grid coverage in the areas of interest. Within the Louisiana Southeast grid, a

full-plane STWAVE grid was nested to cover the Lake Borgne area (Figure 11). The input for each grid includes the bathymetry (interpolated from the ADCIRC domain), surge fields (interpolated from ADCIRC surge fields), and wind (interpolated from the ADCIRC wind fields, which apply land effects to wind fields). The wind applied in STWAVE is spatially and temporally variable for all domains. STWAVE was run at 30-min intervals from 28 August at 1200 UTC to 30 August at 1130 UTC.

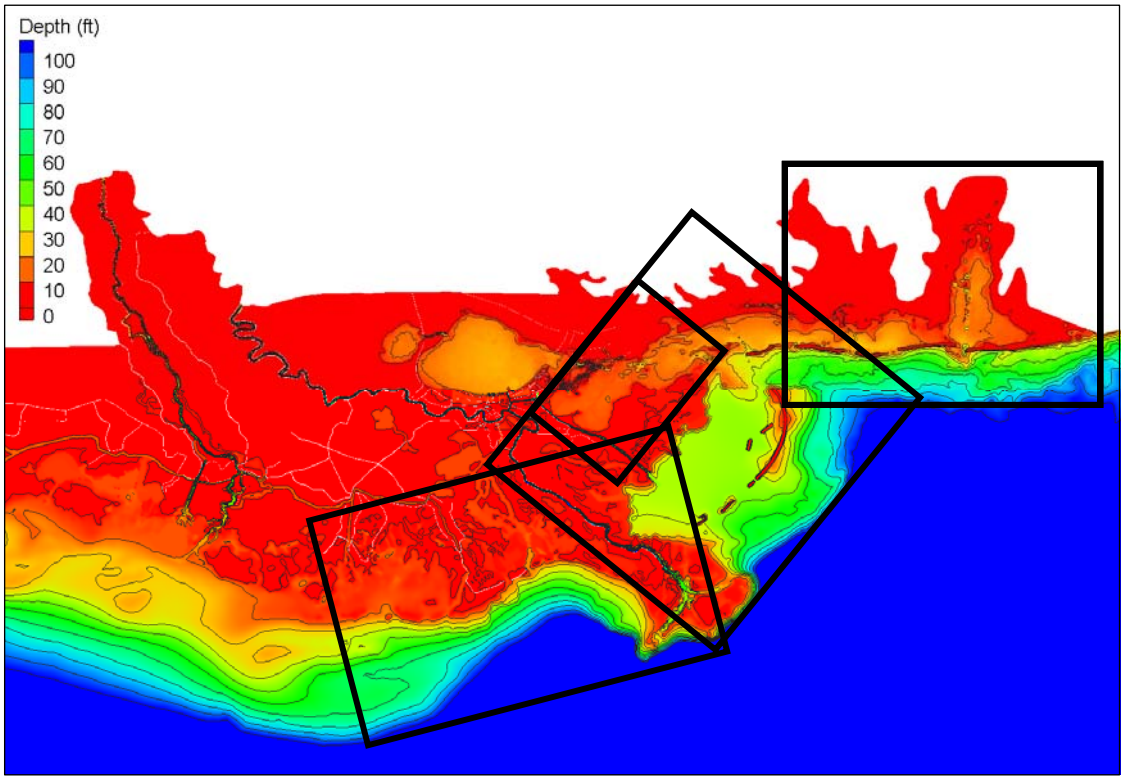


Figure 11. STWAVE modeling domains.

C. Louisiana Southeast and South Grids and Mississippi/Alabama Grid

The half-plane grids cover the coastal area east, southeast, and south of New Orleans at a resolution of 656 ft (200 m). The domain for the Louisiana southeast grid is approximately 84.9 by 92.4 miles (136.6 by 148.8 km) and extends from Mississippi

Sound in the northeast to the Mississippi River in the southwest. The domain for the Louisiana south grid is approximately 82.5 by 104.2 miles (132.8 by 167.8 km) and extends from the Mississippi River in the east to the Atchafalaya River in the west. The domain for the Mississippi and Alabama coasts was added to simulate the wave momentum fluxes that increase the surge in Mississippi Sound and Lake Pontchartrain. The Mississippi/Alabama domain is approximately 70.0 by 75.2 miles (112.6 by 121.0 km) and extends from east of Mobile Bay to Biloxi, Mississippi. These three grids are run with the half-plane STWAVE for computational efficiency. The grid parameters are given in Table 2. Figures 12 to 14 show the bathymetry for the Louisiana southeast, Louisiana south, and Mississippi/Alabama grids, respectively, for Scenario 1 (Katrina Real Run). These simulations are forced with both the local winds and wave spectra interpolated on the offshore boundary from the regional WAM model.

Table 2
STWAVE Grid Specifications

Grid	State Plane	X origin ft	Y origin ft	Δx ft	Δx ft	Orient Deg	X cells	Y cells
Louisiana Southeast	LA Offshore	4294586.6	1639491.5	656	656	141	683	744
Louisiana South	LA Offshore	3997126.0	1264895.0	656	656	108	664	839
Mississippi/ Alabama	LA Offshore	4463976.4	1653950.1	656	656	90	563	605
Louisiana Southeast FP nest	LA Offshore	3976285.2	1725003.4	656	656	141	224	405

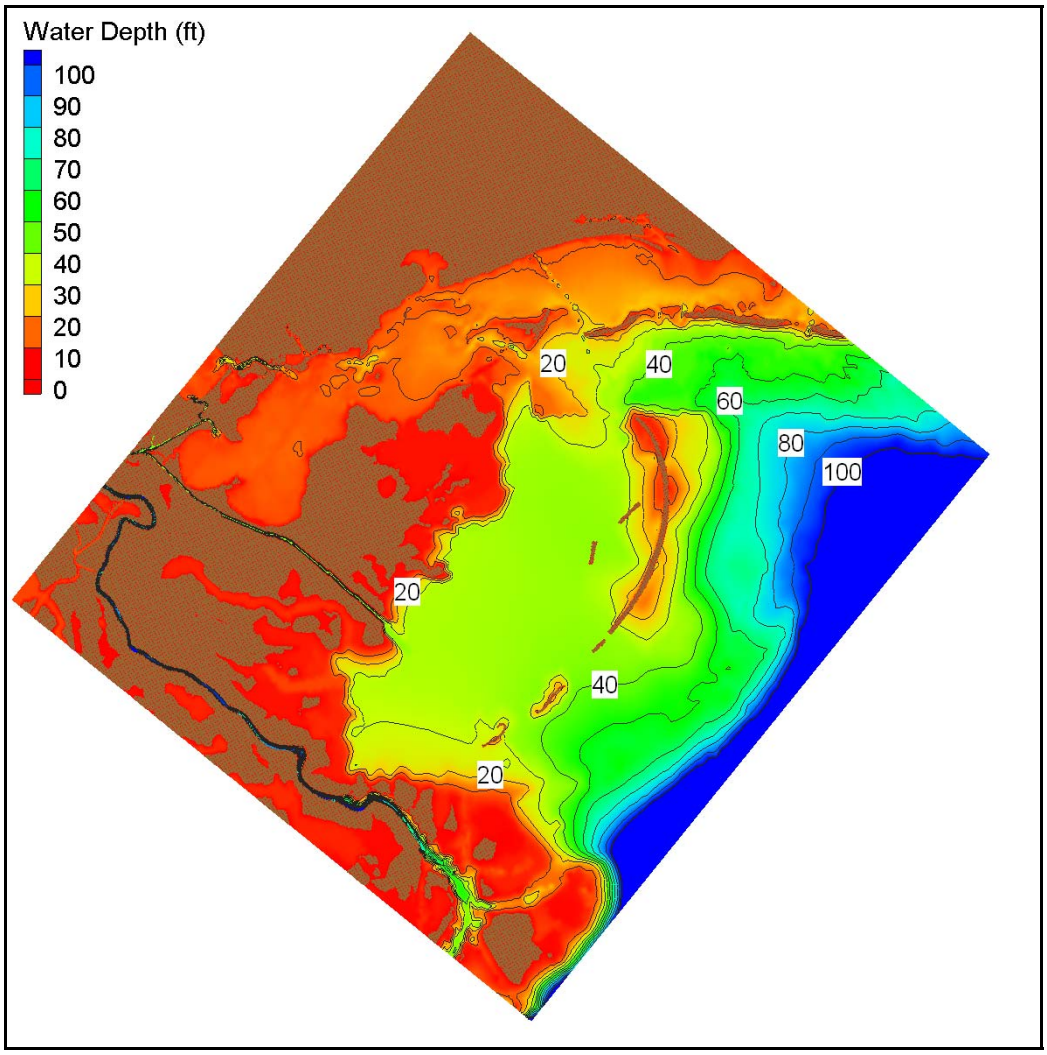


Figure 12. Louisiana Southeast bathymetry grid for Scenario H1 (depths in feet, NGVD 29).

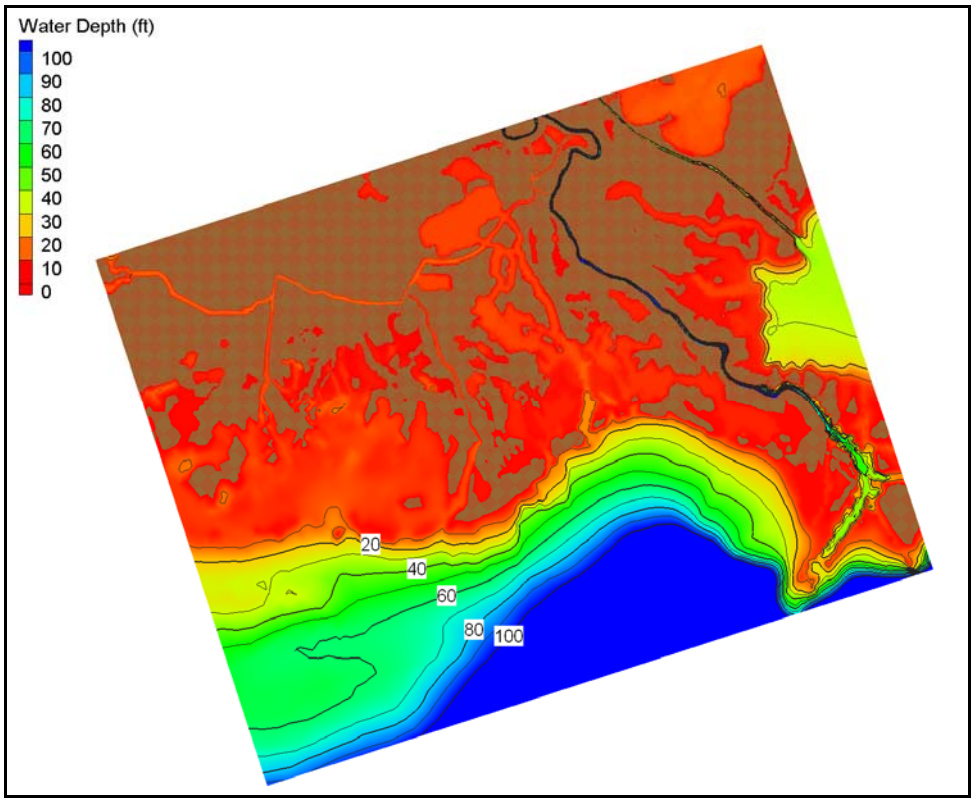


Figure 13. Louisiana South bathymetry grid for Scenario H1 (depths in feet, NGVD 29).

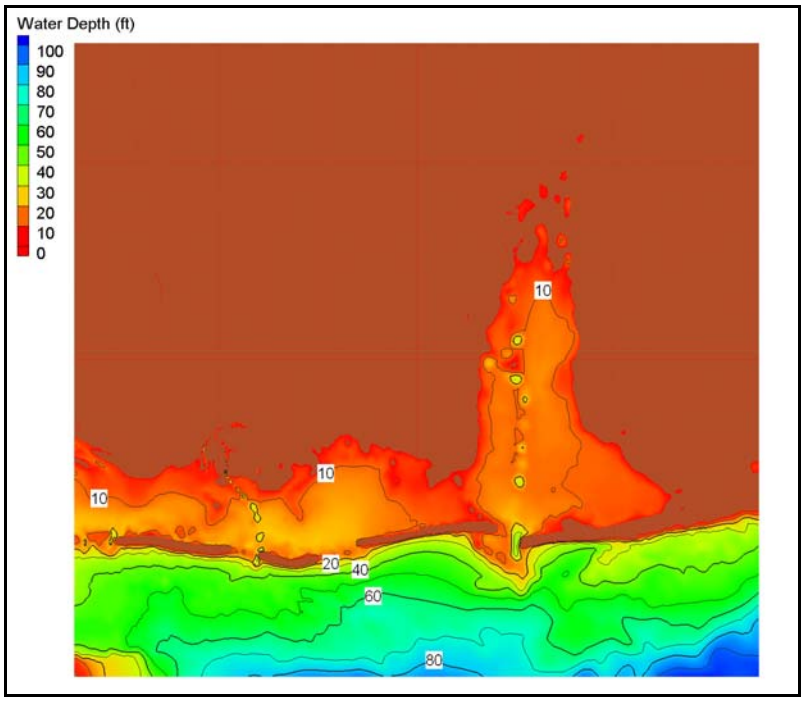


Figure 14. Mississippi/Alabama bathymetry grid for Scenario H1(depths in feet, NGVD 29).

D. Louisiana Southeast Full-Plane Nested Grid

The full-plane grids cover the nearshore area around Lake Borgne at a resolution of 656 ft (200 m). The domain for the Louisiana southeast grid is approximately 27.8 by 50.3 miles (44.8 by 81 km). The wave forcing boundary conditions for this grid are taken from the Louisiana southeast grid. Wind and surge fields are also input from the ADCIRC model. Figure 15 shows the bathymetry for the Louisiana southeast full-plane nested grid for Scenario 1 (Katrina Real Run). Contours of maximum wave heights for each or the six alternatives are shown in Figures 16-21. The vectors indicate the mean wave direction and the color contours represent wave height in feet. At points relatively close to the levees, these maxima occur during the storm interval that waves are propagating toward the levees; while at other points farther away from the levees, they occur during the interval when the winds are blowing away from the levees and hence are propagating away from the coast.

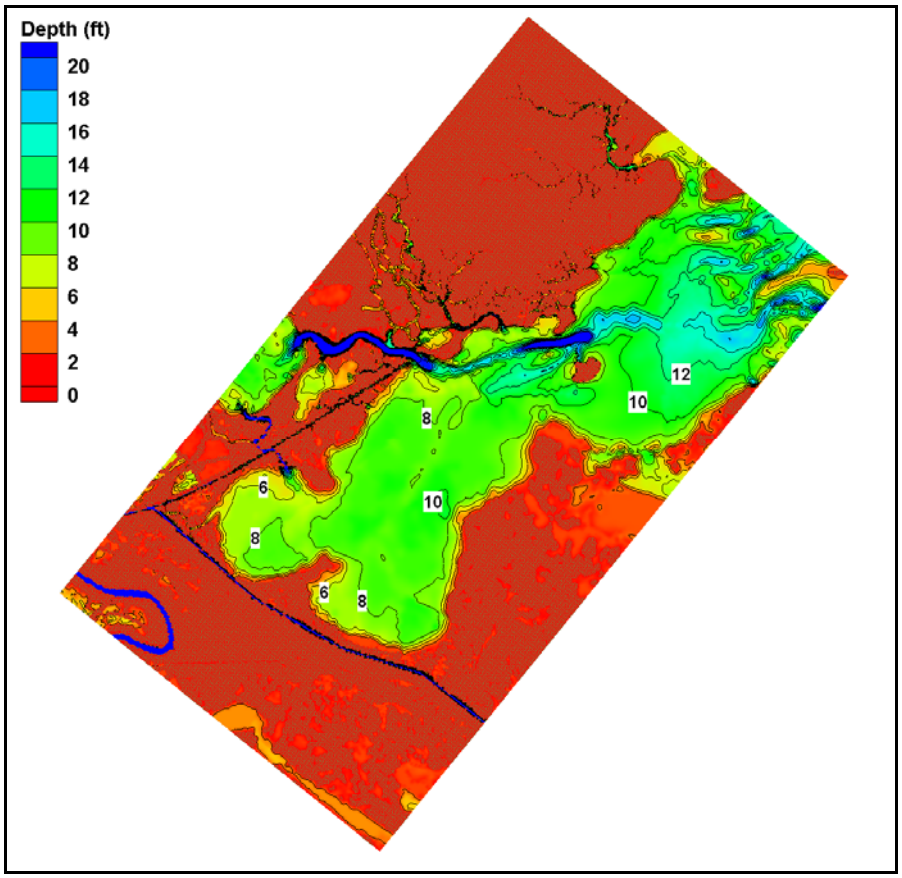


Figure 15. Southeast nested full-plane bathymetry grid for Scenario H1(depths in feet, NGVD 29).

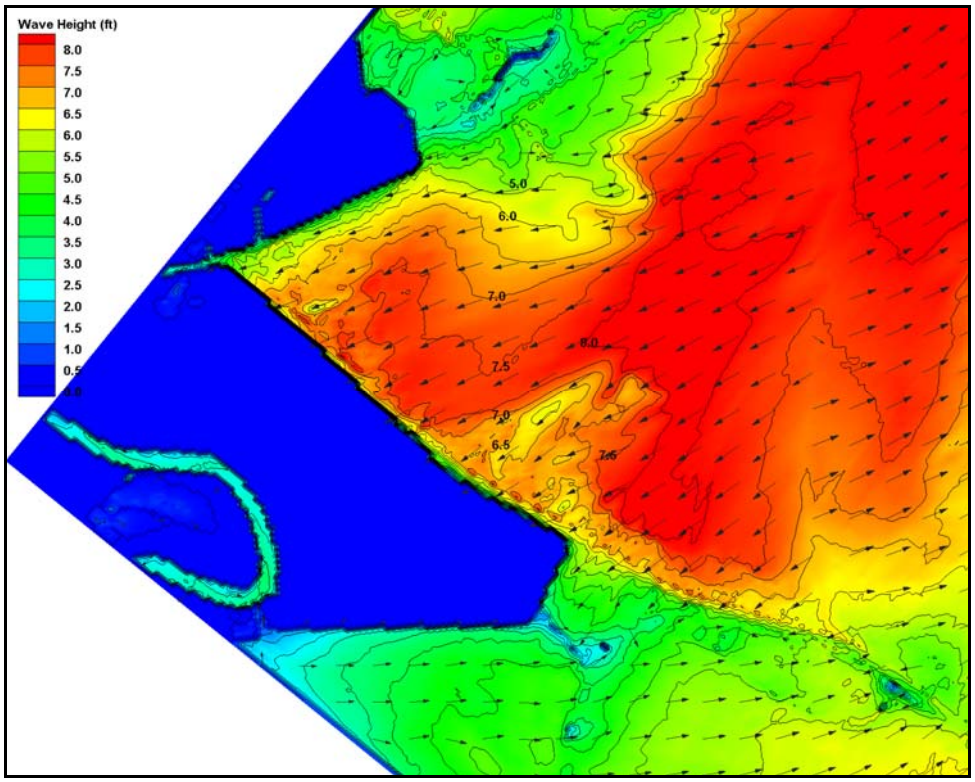


Figure16. Southeast nested full-plane maximum wave heights for Scenario H1 (wave height in feet).

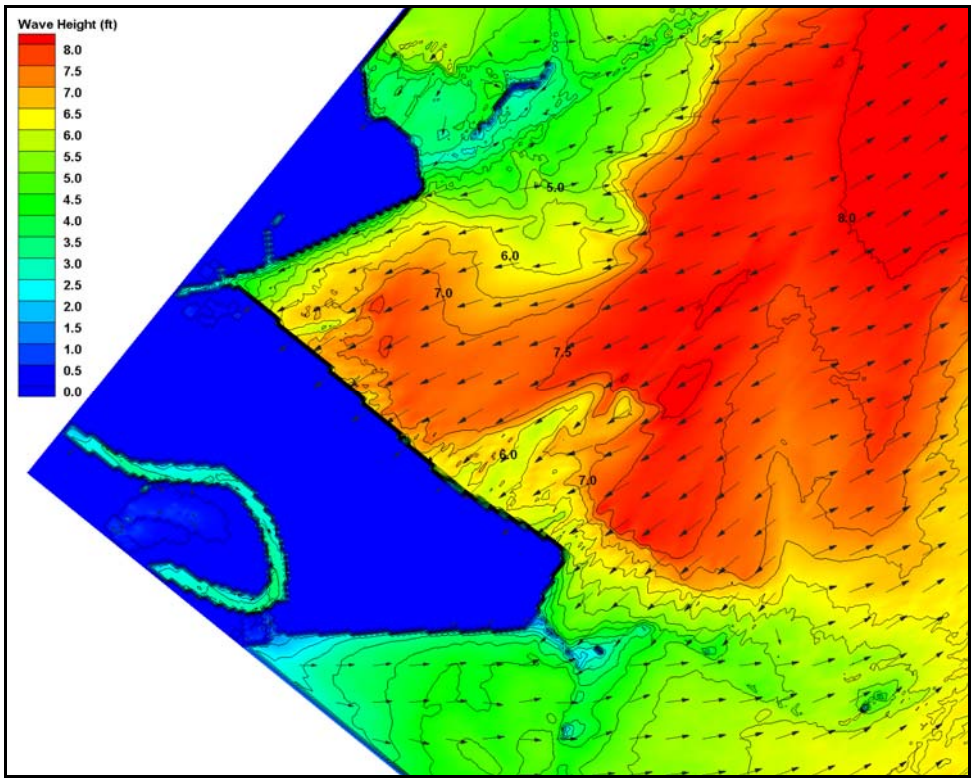


Figure 17. Southeast nested full-plane maximum wave heights for Scenario H2 (wave height in feet).

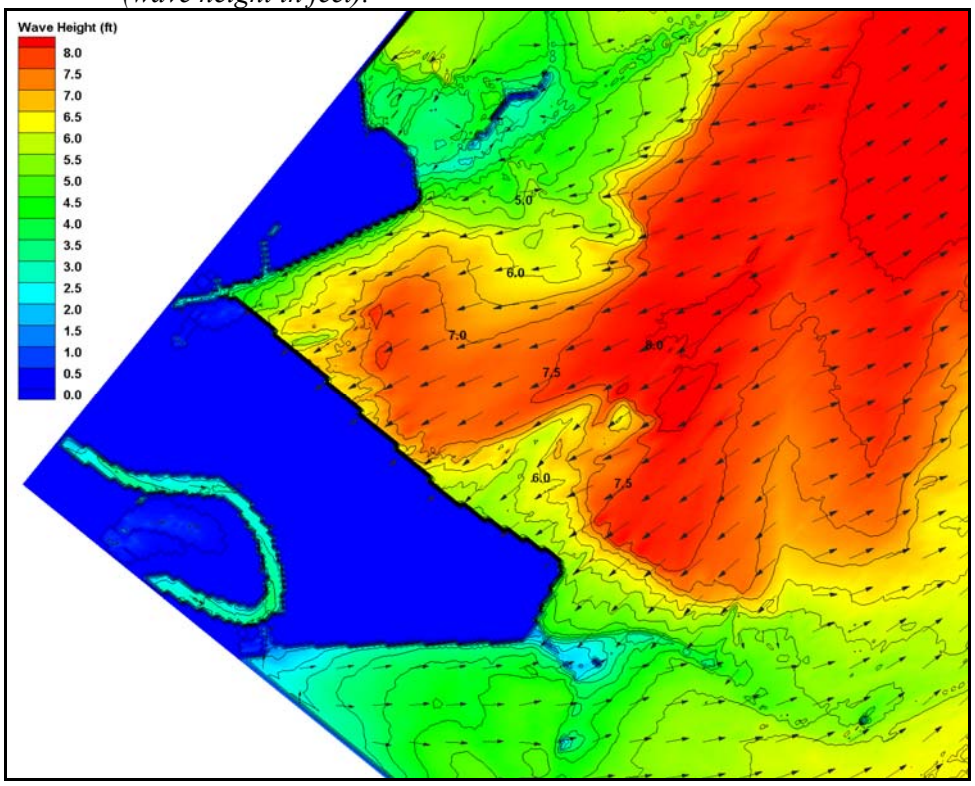


Figure 18. Southeast nested full-plane maximum wave heights for Scenario H3 (wave height in feet).

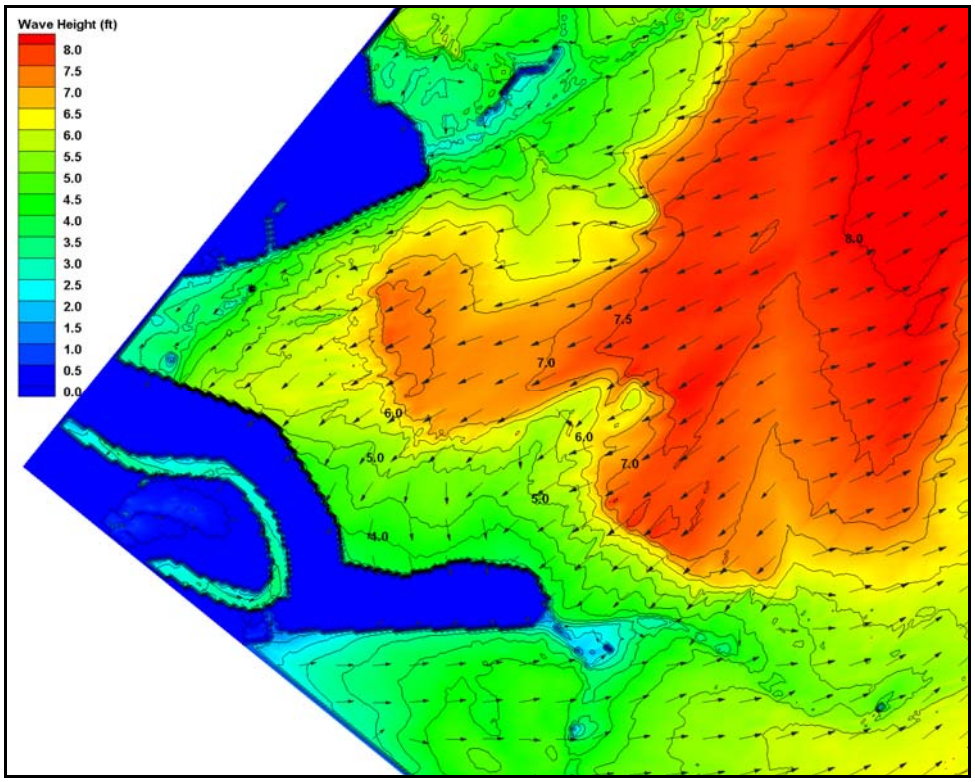


Figure 19. Southeast nested full-plane maximum wave heights for Scenario H4 (wave height in feet).

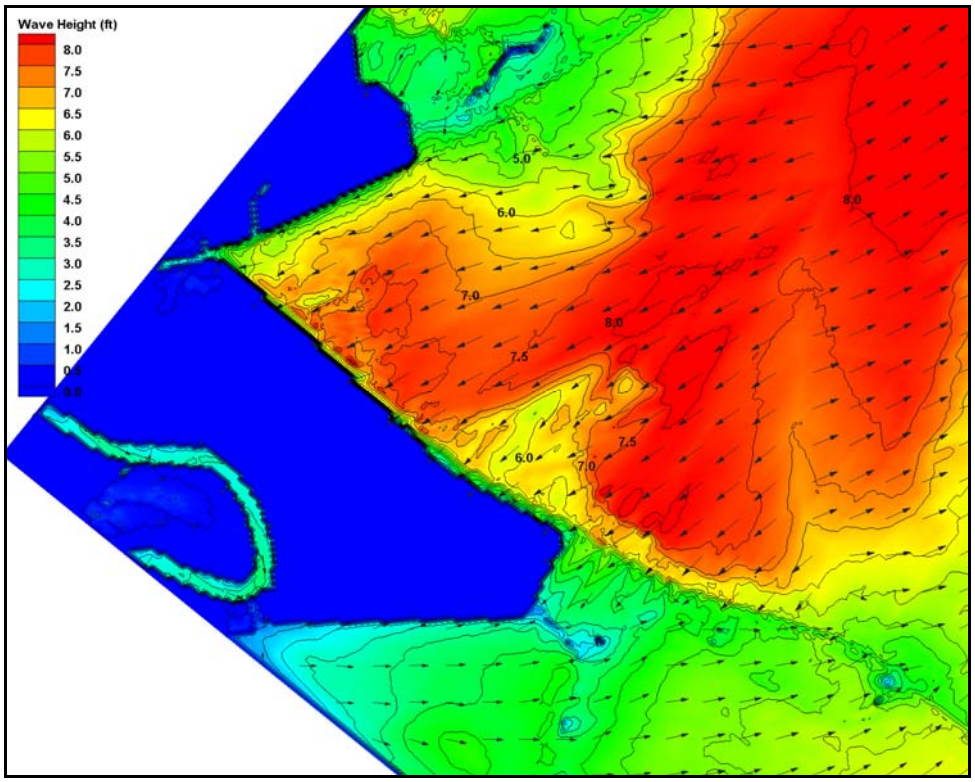


Figure 20. Southeast nested full-plane maximum wave heights for Scenario H5 (wave height in feet).

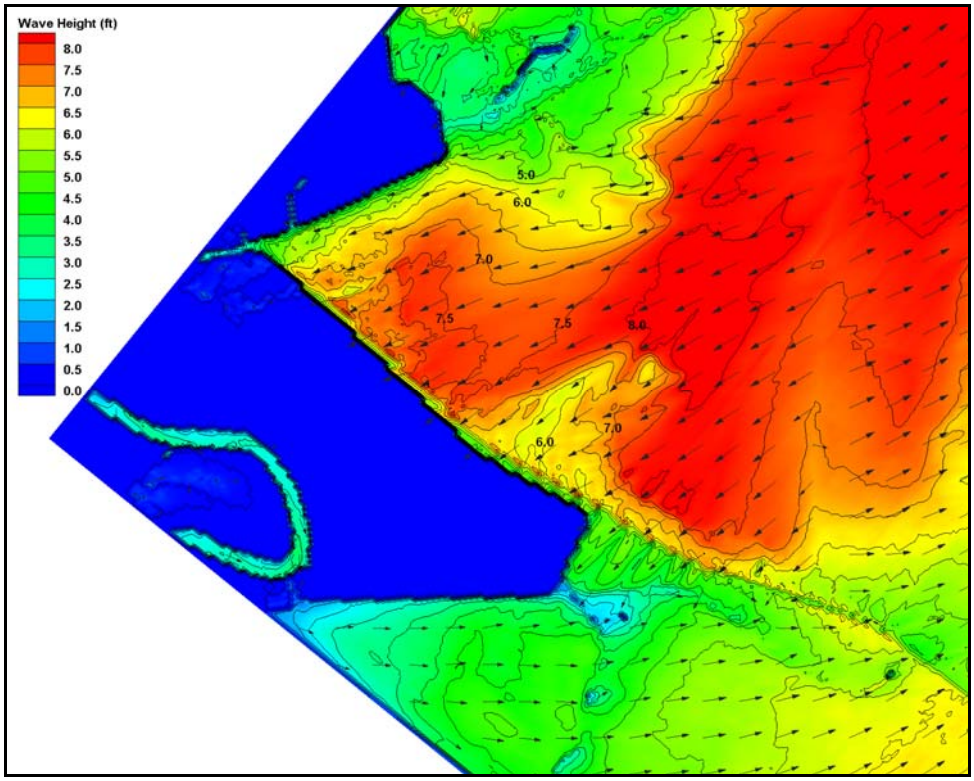


Figure 21. Southeast nested full-plane maximum wave heights for Scenario H6 (wave height in feet).

E. STWAVE Simulations

STWAVE simulations on the half-plane grids were run in parallel following the initial ADCIRC run. Input bathymetry and friction factor (Manning n values) were interpolated from the ADCIRC grid for each scenario (changes occurred in only the Louisiana southeast and Louisiana full-plane nested grids). Time-varying surge and wind fields were also interpolated onto the STWAVE grids at 30-minute increments. Boundary wave spectra from the Louisiana southeast grid were used to force the Louisiana full-plane nested grid. Wave conditions along the MRGO from the full-plane STWAVE simulation were then fed into the COULWAVE simulations.

F. Results for Louisiana Southeast Full-Plane Nested Grid and Boundary Conditions Passed to the Boussinesq Model

Figure 1 in Section 1 of this report shows the points along the MRGO that were used to drive the Boussinesq simulations that will be described in the next section. These

21 points provide a reasonable resolution of all wave and surge processes affected the levees along Reach 2. At each point, significant wave heights, spectral peak wave periods, and mean wave angles were output at 30-minute intervals for a 48-hour time period encompassing the storm.

3.3 Boussinesq Model Application for the Estimation of Setup, Overtopping, and Velocities Along Reach 2 of the MRGO

Boussinesq equations have been developed for application to waves in coastal environments since the 1960's and 1970's, with Whitham (1967) and Peregrine (1972) establishing some of the early foundations that showed the applicability of these equations to coastal water waves. Many excellent articles have been published in the scientific literature regarding both the suitability of the Boussinesq equations for application to coastal wave problems and the use of these equations within numerical models for these problems. An important aspect of these models is that they have been well validated in comparisons to field and laboratory data over a wide range of wave conditions in terms of their ability to predict wave setup, overtopping rates, and velocities. The excellent theoretical foundation of these models, their mature stage of model development for applications to coastal water waves, the well-established accuracy of estimates produced by these models, the general acceptance of these models within the oceanographic and coastal engineering community, and the public availability of these models all make this class of model a superb choice for critical applications relating to hurricane-generated waves incident on levees. This is the reason that this type of model was used in the Katrina simulations by the IPET "detailed-hydrodynamics" team and is also the reason that it is chosen for present application in this report.

The Cornell University Long and Intermediate Wave Model (COULWAVE) was chosen for this application, since results from its application in the IPET study have been reviewed by the National Research Council and found to be very satisfactory. This model was initially developed by a group at Cornell University and, as seen in the small sample of publications, included in Appendix B, has been shown to work well for predictions of wave run-up on beaches, slopes, and other structures.

A. Application of COULWAVE to the Reach 2 Along the MRGO

In order for these models to be applicable to typical wave conditions generated by hurricanes, as noted in Section 2.2 of this report, it is essential that the models be driven by irregular (spectral) wave conditions at the incident wave boundary. Since such boundary conditions contain waves which vary naturally over time, it is important to run sufficient time to allow the results to attain a stable value. Tests during the IPET study showed that this required approximately 20-minutes of simulated time for each model simulation. Given that computer runs had to be made for 6 different scenarios, for 21 points along Reach 2, for 95 time steps each, and for 20-minutes of simulated time, it was decided that it would be more efficient to develop a suitable look-up table from a set of runs than to keep running the Boussinesq code over and over. For the purpose of examining wave transformations and associated wave setup and overtopping along Reach 2 in a consistent fashion, a generic configuration of the Reach 2 levee was developed. Sensitivity tests were then performed to ensure that this representation would produce accurate results when the Boussinesq model was applied to it.

These sensitivity tests showed that Boussinesq simulations converged at a spatial resolution of 2.5 feet, so this value was chosen for all subsequent runs in sensitivity testing as well as the final production runs. A range of levee crest widths was examined and it was found that the range of levee crest widths along Reach 2 only minimally affected wave heights and overtopping rates (less than 5%). A levee crest width of 15 feet was used in all final runs. Another factor investigated in these tests was the width of the shelf in between the MRGO and the toe of the levee. Values of 150 feet to 1200 feet were considered and the results showed that the wave heights and overtopping rates on the levee varied by only 10% for all of these simulations. A value of 200 feet was selected for our generic profile. Finally, after investigating the behavior of wave heights and overtopping a range of slopes (from zero to 1:50) over this 200-ft shelf and noting that the relative sensitivity of wave setup and overtopping to variations in slope tended to be quite small, it was decided that this relatively short, generic "shelf" section in this profile should be flat with an elevation of 7 feet. Beyond the toe of the levee, a constant levee slope of 1:5 was used up to the specified elevation of the levee (taken to have a nominal value of 17.5 feet) and after the 15-ft crest section, the same 1:5 slope was used to represent the protected side of the levee back to a 7-ft elevation.

The incident-wave boundary was specified in a region that was 30 feet deep and allowed to run up to the beginning of our generic shelf over a distance of 300 feet and was set in a manner that allowed reflected waves to pass back through this boundary location rather than to be re-reflected. Given the relatively short wavelengths of the waves in this study, it was observed that very little of the total transformation occurred over this 1:10 slope. The generic profile (Figure 23) used here should provide a

consistent representation of the area along Reach 2 for the purpose of inter-comparing the different scenarios presented in Table 1. Figure 24 shows a “snapshot” of one of the simulated water surfaces at a time when the mean water elevation is above the levee crest.

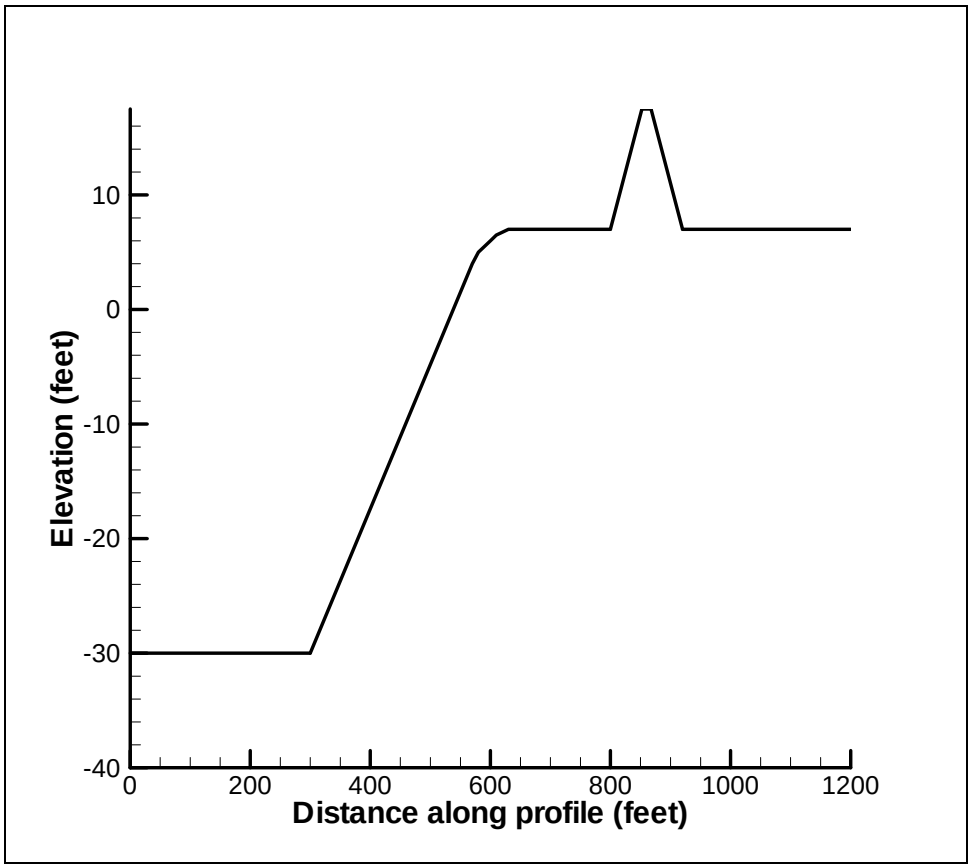


Figure 23. Generic profile for Boussinesq simulations with COULWAVE.

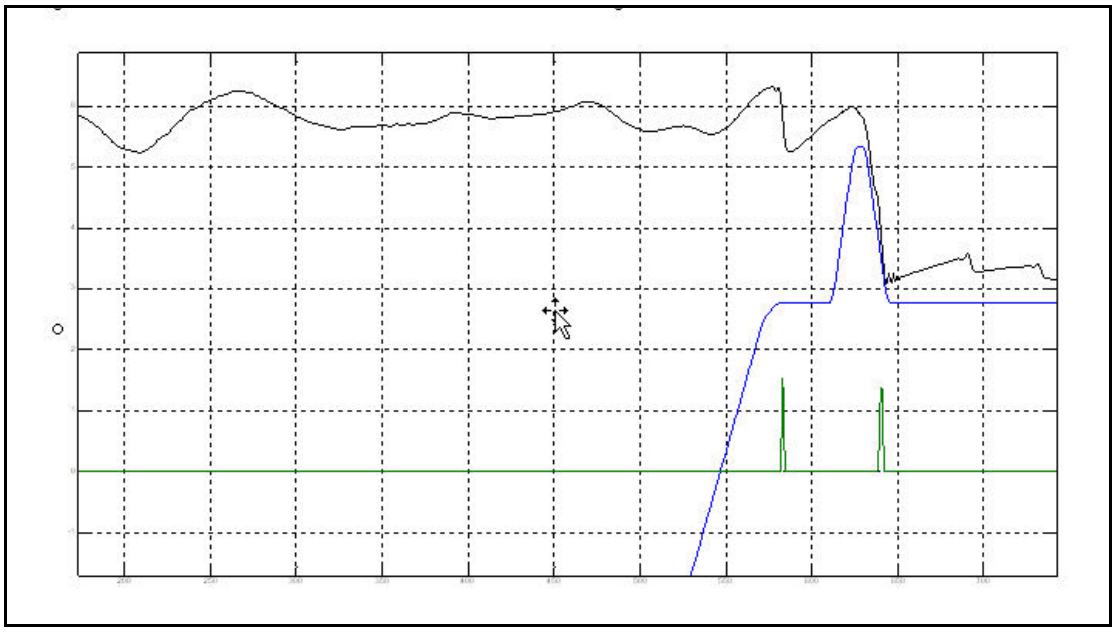


Figure 24. Snapshot of water surface from Boussinesq simulation over generic profile The green spikes denote strong wave breaking episodes.

Incident waves were run for a number of significant wave heights (0, 2, 4, 6, and 8 feet), a number of spectral peak wave periods (6, 8, and 12 seconds) and a number of relative freeboards (-4, -2, 0 , and 2 feet). For relative freeboards greater than 2 feet, estimates of the overtopping rates were extrapolated using a "3/2" power law, consistent with a "weir equation" formulation. Wave directions were all considered to be propagating directly along the profile for these runs. For each simulation in this set, total overtopping rates, wave generated velocities, and wave setup were calculated. Given a value of wave height, wave period, and relative freeboard an interpolated/extrapolated estimate of total overtopping rates, wave generated velocities, and wave setup can be obtained. This "lookup table" approach simplifies the modeling and computational effort while maintaining good accuracy for all estimated values.

The time series of wave heights, periods and surge elevations were obtained from the STWAVE runs (since the STWAVE runs already had incorporated the surge

elevations from the ADCIRC runs described in Westerink, 2008) at each of the 21 points shown in Figure 1 for all six scenarios. For the Boussinesq runs performed here, all surge elevations along Reach 2 were scaled by a multiplicative 1.12 factor to bring the simulated surges in line with observed high water marks in this area (Figure 24). The wave periods in the Boussinesq lookup table were referenced in terms of spectral peak wave period; whereas, the wave periods in the STWAVE outputs were given in terms of mean wave periods. For the spectral shapes characteristic of the STWAVE model at the boundary, a multiplicative conversion factor of 1.15 was used to convert the STWAVE mean periods into spectral peak periods for referencing the lookup table information. Although the surges are seen to vary quite smoothly along this Reach, the levee crest elevations vary substantially at a localized scale. Given the large variability of the levee crest elevations along Reach 2 seen in this figure, it was decided that it was not very representative to consider only a single value for the levee crest elevation at each of these 21 points; consequently, it was decided to characterize each of the 21 locations along Reach 2 by three different levee crest elevations: a characteristic value representing the 25% lowest levee crest elevations at each of these points, a characteristic value representing the intermediate 50% of levee crest elevations at each of these points, and a characteristic value representing the highest 25% of levee crest elevations at each of these points.

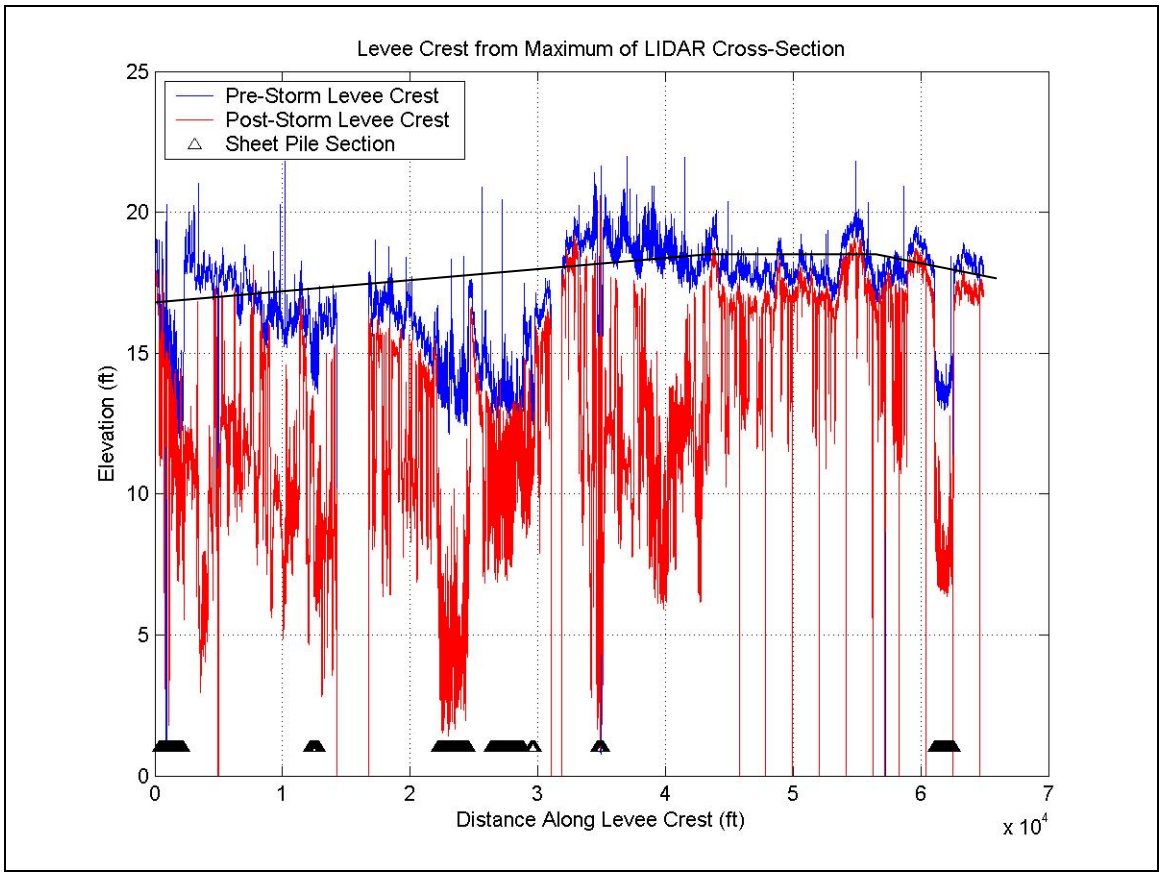


Figure 24. Maximum surges along Reach 2 for Scenario 1 from Ebersole (2008) plotted with pre- and post-Katrina levee crest elevations along Reach 2.

3.4 Estimated Setup and Overtopping Rates, Setup, and Velocities

Detailed scrutiny of the time series generated, which were obtained via the methodology described in the previous section, shows that the results for all points along Reach 2 have very similar temporal characteristics. This is not surprising since all of these points had similar exposures to the waves approaching out of the east-southeast. Also, since the same sequence of winds was used for each scenario simulated, it was seen that the temporal characteristics for the different scenarios were all quite similar. Thus, for the sake of brevity, only information on the maximum values of different parameters will be shown and discussed here. Table 3 contains the estimated maximum surge elevations and levee crest elevations for the portions of the levees discussed in the

previous section and the maximum overtopping rates in cubic feet per second per foot along the levee crest for Scenario 1 (existing conditions at the time of Hurricane Katrina). It should be noted that the term "maximum" used in this section always refers to quantities that are representative of a 30-minute interval; thus, the maximum value is actually the maximum 30-minute average value. As can be seen in this table, the overtopping rates for the lowest 25% of the levee crests can be from 50% to over 400% greater than the overtopping rates for the median 50% of the levee elevations. This clearly supports the decision made in this report not to treat these levees as having a constant crest elevation. Maximum overtopping rates that exceeded 1 cfs/ft are highlighted as either lighter or darker gray shaded cells. The light blue highlighting shows those sections for which the surge level exceeds the elevation by at least 1 foot.

Table 3. Along-Levee Variation of Maximum (30-minute) Overtopping Rate

Point #	Maximum Total Water Level (ft)	Levee Crest Elevation (ft)			Overtopping Rate (cfs/ft)			
		Lower 25%	Median 50%	Higher 25%	Lower 25%	Median 50 %	Higher 25%	Weighted Average
1	16.8	11.0	15.3	16	39	4.9	2.1	12.6
2	17.3	17.6	18.0	18.5	1.2	0.7	0.2	0.7
3	17.5	14.0	16.5	17.7	17.9	3.8	1.7	6.8
4	17.6	15.5	16.4	17.0	8.2	4.4	2.5	4.9
5	17.9	15.5	16.2	17.0	9.3	6.3	3.0	6.2
6	18.0	15.7	16.5	17.3	9.1	5.7	2.8	5.8
7	17.8	15.4	15.7	16.0	10.2	8.9	7.6	8.9
8	18.0	15.0	16.2	17.0	13.4	7.4	4.0	8.0
9	18.0	15.0	16.6	18.4	13.2	5.5	1.4	6.4
10	18.3	14.0	17.0	19.0	25.0	4.5	1.0	8.8
11	18.2	17.5	18.0	18.5	2.8	2.2	1.5	2.2
12	18.1	17.0	17.7	18.4	4.0	2.3	1.4	2.5
13	18.2	17.1	17.6	18.1	3.9	2.4	1.8	2.6
14	18.3	17.5	18.0	19.0	2.6	2.0	0.9	1.9
15	18.2	17.6	17.9	18.4	2.4	2.0	1.5	2.0
16	18.2	14.0	16.8	18.3	24.9	5.4	1.6	9.3
17	18.2	17.3	17.8	18.6	3.0	2.1	1.2	2.1
18	18.1	18.2	18.5	18.8	1.6	1.2	0.9	1.2
19	17.8	17.8	18.3	18.8	1.7	1.1	0.6	1.1
20	17.7	14.5	17.0	18.0	14.4	2.5	1.3	5.2
21	17.5	17.0	17.3	17.5	2.3	1.9	1.7	1.9

Table 3 also shows that overtopping rates vary substantially from point to point along Reach 2, indicating that such spatial variability must be considered in any attempt to understand levee response, overtopping rates, and associated flooding in the protected area behind these levees. As an example of this, the median overtopping rates in Table 3 are seen to vary by more than an order of magnitude between the smallest overtopping rates and largest overtopping rates along this Reach. Figure 25 shows the variation of maximum surge levels and significant wave heights, along with associated mean wave periods at the time of maximum waves, along Reach 2 for Scenario 1 from the STWAVE simulations. As can be seen here, except at Point 1, all of the wave heights are essentially in a 1.5-foot range from 5.5 to 7 feet with peak surge levels varying by about the same amount (18.3-19.8 feet). Similarly, except for Point 1, wave periods along this Reach remain relatively constant (4.8-5.8 seconds). Thus, it is apparent that the dominant source of variations in the overtopping rates along Reach 2, as seen in Table 3, are not due to variations in the surge and wave characteristics but, instead, must be due to differences in the elevations of the levee crests along this Reach.

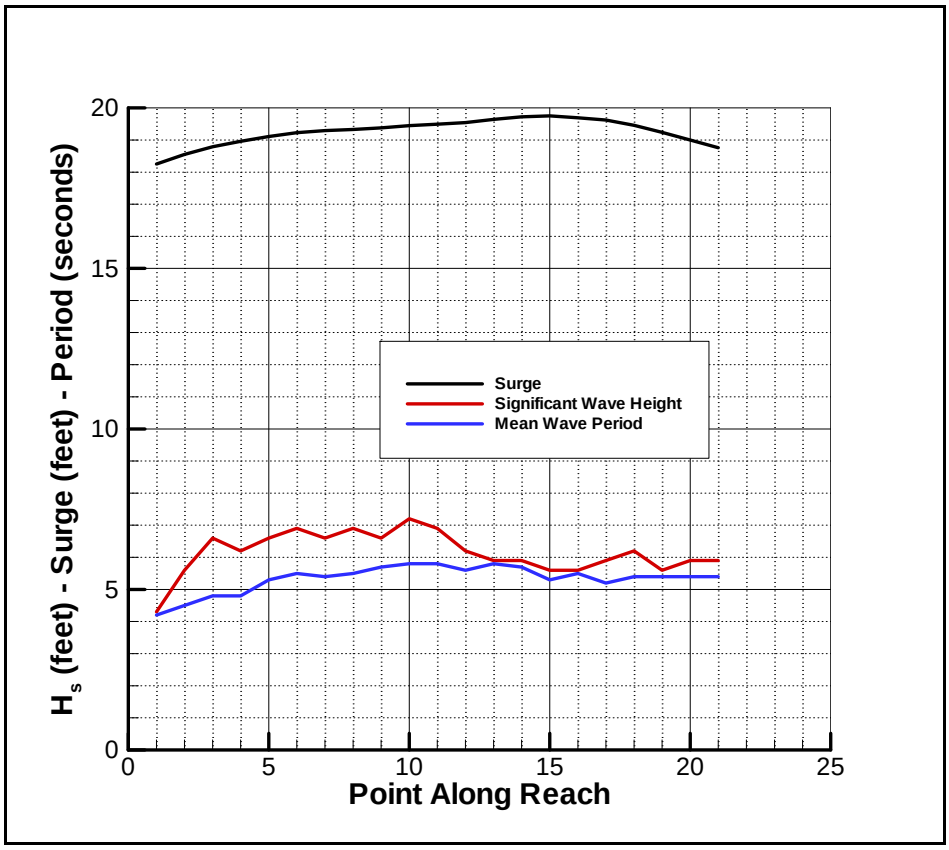


Figure 25. Peak surge levels and significant wave heights, and wave periods coincident with the peak wave heights, along Reach 2 for Scenario 1.

Additional examination of Table 3 shows that the maximum overtopping rates are highly correlated with the difference in the surge and levee-crest elevations (freeboard). In the IPET study (Volume IV of the IPET Report), it was noted that waves contributed very significantly to overtopping rates up to about ½ to 1 foot of freeboard. For higher freeboards, overtopping was primarily controlled by the level of water above the levee, for water levels behind the levee that are lower than the levee crest. Given the magnitudes of the freeboards associated with the overtopping along Reach 2, it is not surprising that the overtopping rates are primarily driven by the freeboard, with only a minor dependence on the wave heights along this Reach.

A. Comparison of Overtopping for different scenarios

Figure 26 shows a comparison of peak surges and incident wave heights, along with the mean periods coincident with the time of maximum wave height, for points along Reach 2. As can be seen in this figure, maximum surges, waves, and the associated wave periods seem consistent for all of the scenarios simulated. The one exception is found in Scenario 4 where the surges are, in general, about 1.5 feet lower than the surges for the other scenarios. The maximum wave heights in Scenarios 2-6 vary by less than 1 foot from the maximum wave heights in Scenario 1; and the associated wave periods vary by only about 0.5 seconds.

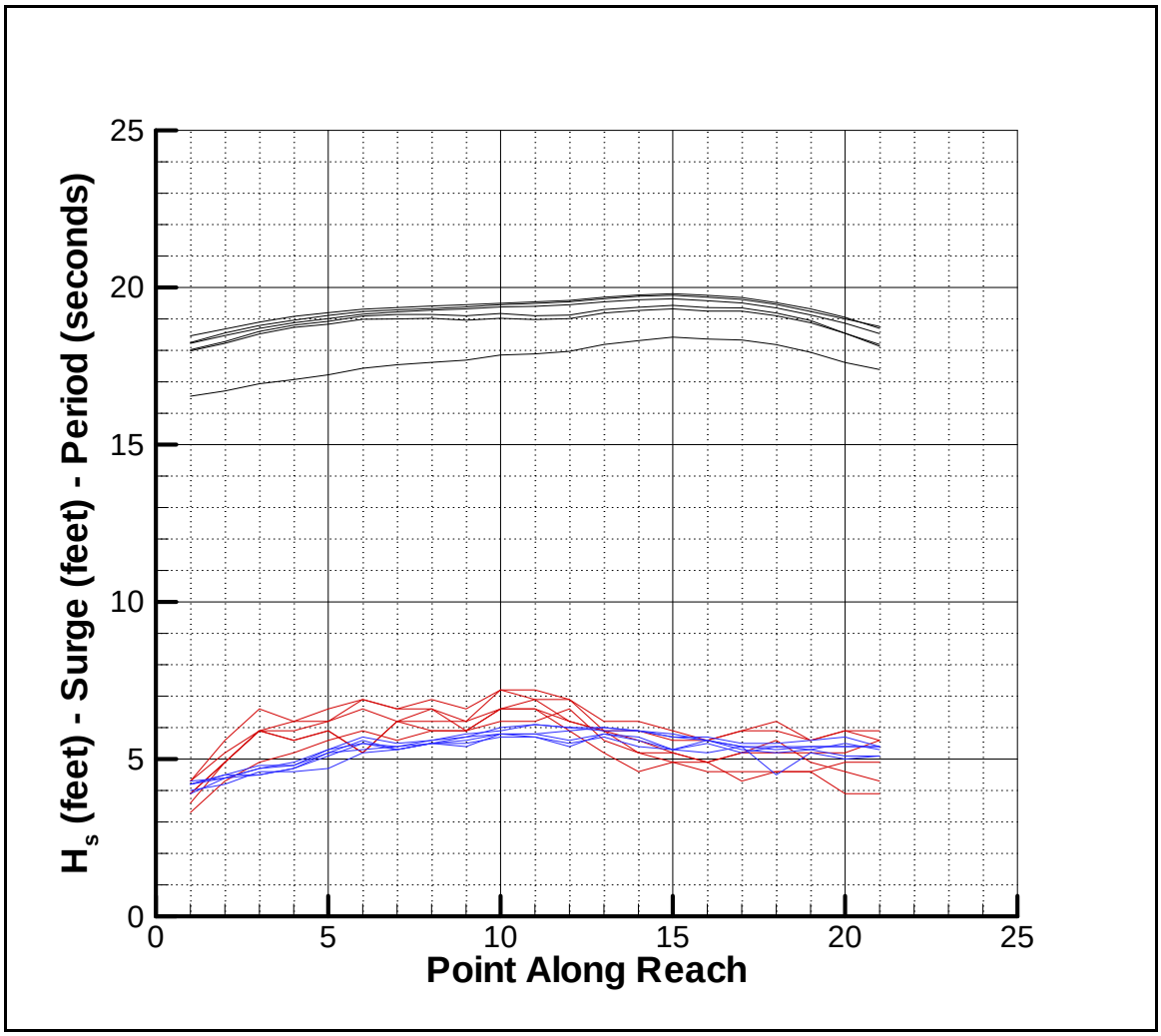


Figure 26. Comparison of maximum surge levels and significant wave heights, along with mean wave periods associated with the time of maximum waves, along Reach 2 for all six scenarios simulated in this study. Black lines denote the surge values; red lines denote the significant wave heights; and blue lines denote the wave periods.

Figure 27 gives the maximum overtopping rates along Reach 2 for all six scenarios. As can be seen here, the differences, other than for Scenario 4, are quite small. Given that the levee crest elevations were held constant in all of these simulations and that the maximum overtopping rates are in the regime where they are dominated by the mean flow over the levee rather than pulsating wave-driven overtopping, the similarity in the overtopping rates for the different scenarios is not very surprising. In this flow

regime, the role of waves in contributing to overtopping is very limited; consequently, the small differences in wave heights shown in Figure 27 would have very minor effects on the total volumes entering the protected area behind Reach 2.

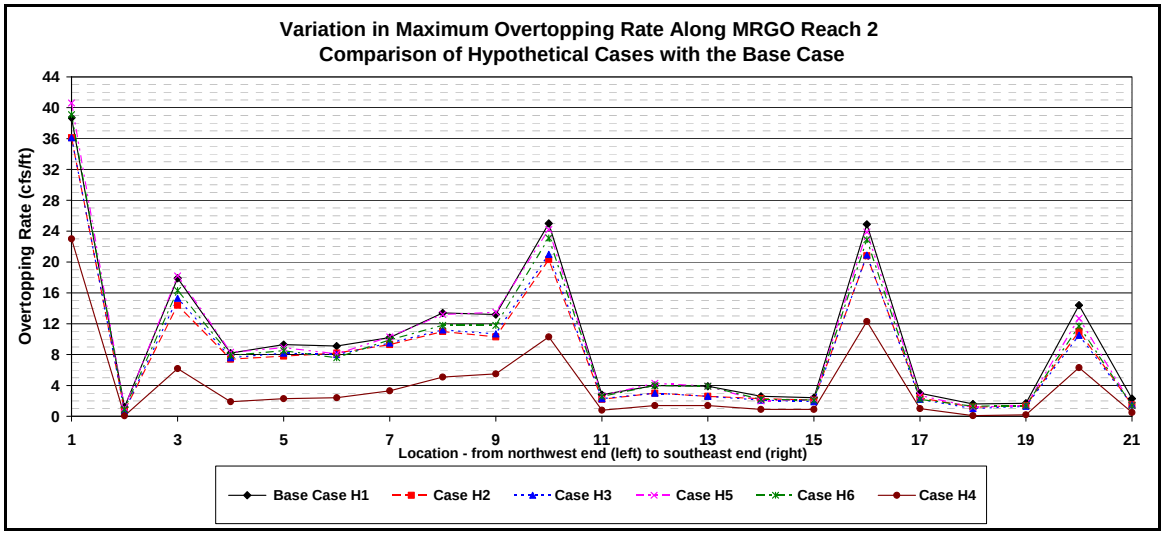


Figure 27. Variation of maximum overtopping rates along Reach 2 for all six scenarios.

It should be noted that this treatment of Scenario 4 is somewhat different than the description in Table 1. In that Table a single levee elevation of 17.5 feet was assumed, but this would not be appropriate for a comparison of the wave and surge effects. Thus, for Scenario 4 in this figure, the levee crest elevations were assumed to have the same values as used in the simulations for the other scenarios. Even in this scenario, the overtopping rates are substantial and are well above the widely accepted "no-damage" thresholds of 0.1 cfs/ft.

A complete set of outputs from the Boussinesq simulations (the time series of half-hourly overtopping rates, velocity information, and setup) was provided to the interior drainage team for their utilization (Fitzgerald, 2008).

References

Booij, N., Haagsma, I J. G., Holthuijsen, L. H., Kieftenburg, A.T.M.M., Ris, R. C., van der Westhuysen, A. J., and Zijlema, M. 2004. "SWAN Cycle III Version 40.41 Users Manual," Delft University of Technology, Delft, The Netherlands, 118 p, http://fluidmechanics.tudelft.nl/swan/index.htm.

Booij, N., Ris, R. C., and Holthuijsen, L. H. 1999. "A Third-Generation Wave Model for Coastal Regions, Part I: Model Description and Validation," J. Geophys. Res., 104(C4), 7649-7666.

Fonseca, M.S. and Cahalan, J.A. 1992: A preliminary evaluation of wave attenuation for four species of seagrass. Estuarine Coastal Shelf Sci. 35. 565-576.

Knutson, P.L., Seelig, W.N. and Inskeep, M.R., 1982: Wave damping in *Spartina Alterniflora* marshes. Welands, 2, 87 – 104.

Smith, J. M. 2007. Full-plane STWAVE: II. Model overview. ERDC TN-SWWRP-07-5. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil/library/publications/chetn/pdf/chetn-i-75.pdf

Smith, S. J., and Smith, J. M. 2001. "Numerical Modeling of Waves at Ponce de Leon Inlet, Florida." J. Waterway, Port, Coastal and Ocean Engineering, 127(3), 176-184.

Smith, J. M., Sherlock, A. R. and Resio, D. T. 2001. "STWAVE: Steady-State Spectral Wave Model User's manual for STWAVE, Version 3.0," ERDC/CHL SR-01-1, US Army Corps of Engineers Engineer Research and Development Center, Vicksburg, MS.

Thompson, E. F., Smith, J. M., and Miller, H. C. 2004. “Wave Transformation Modeling at Cape Fear River Entrance, North Carolina.” J. Coastal Research, 20 (4), 1135-1154.

van der Westhuysen, A.J, Zijlema, M., Battjes, J.A. 2007. “Nonlinear saturation-based whitecapping dissipation in SWAN for deep and shallow water.” J. Coastal Engr. 54, 151-170.

Peregrine, D.H. 1972. “Equations for Water Waves and the Approximation Behind Them.” Waves on Beaches and Resulting Sediment Transport. R.E. Meyer, ed., Academic Press, pp 95-121

Whitham, G.B. 1967. “Variational Methods and Applications to Water Waves.” Proc. Roy. Soc. London, Series A, Vol 299, pp 6-25

APPENDIX A

Donald Thomas Resio
Peer-Reviewed Publications in last 10 years (1999 – 2008)

Resio, D.T., Swail, V.R., Jensen, R.E., and V.J. Cardone, 1999: Wind speed scaling in fully-developed seas. J. Phys. Oceanogr., 29, 1801-1811.

Resio, D.T. and V.J. Cardone, 1999: Wave Climate Modeling, Shore and Beach, 14.

Hwang, P.A., Bratos, S.M., Teague, W.J., Wang, D.W., Jacobs, G.A., and D.T. Resio, 1999: Winds and Waves in the Yellow and East China Sea: A Comparison of Altimeter Measurements and Model Results, J. of Oceanogr.,55, No 2, 307-325.

Resio, D.T., Pihl, J., Tracy, B.A. and C.L. Vincent: 2001: Nonlinear Energy Fluxes and the finite-depth equilibrium range in wave spectra, J. Geophys. Res.(Oceans),106, No. C4, 6985-7000.

Onorato, M., Osborne, A.R., Serio,M., Resio, D, Pushkarev, A., Zakharov, V.E., Brandini, C., 2002: Freely Decaying Weak Turbulence for Sea Surface Gravity Waves, The American Physical Society, 89, No. 14, 144501-4.

Pushkarev, A., D. Resio, and V. Zakharov, 2003: Weak turbulence approach to the wind-generated gravity sea waves, Physica D, 184, 29-63.

Resio, D.T., Long, C.E., and C.L. Vincent, 2004: Equilibrium-range constant in wind-generated wave spectra, J. Geophys. Res., (Oceans), 109, C01018.

Pushkarev, A., D. Resio, and V. Zakharov, 2004: Second generation diffusion model of interacting gravity waves on the surface of a deep fluid, Nonlinear Processes in Geophysics (NPG), 11, 329-342.

Long, C.E, and D. Resio, 2007: Wind wave spectral observations in Currituck Sound, North Carolina, J. Geophys. Res. 112, CO5001.

Ebersole, B.A., Resio, D.T., and J. J. Westerink: A Community Approach to Improved Prediction and Characterization of Coastal Storm Hazards, Stemming the Tide of Coastal Disasters, Part 1, Volume 40, Number 4, Winter 2006/2007

A. Korotkevich, A. Pushkarev, D. Resio, and V. Zakharov, 2007: Numerical Verification of the Hasselmann equation, in the book "Tsunami and Nonlinear Waves", Kundu, Anjan (Editor), Springer 2007, Approx. 325 p., 170 illus., Hardcover, ISBN: 978-3-540-71255-8.

Badulin, S.I., Babanin, A.V., Zakharov, V.E., and D. Resio, 2007: Weakly turbulent laws of wind-wave growth, J. Fluid Mech., 591, 339-378.

V.E. Zakharov, A.O. Korotkevich, A. Pushkarev and D. Resio, 2007: Coexistence of Weak and Strong Wave Turbulence in a Swell Propagation, Phys.Rev.Letters, 99, 164501.

A.O. Korotkevich, A. Pushkarev, D. Resio and V.E. Zakharov, 2007: Numerical Verification of the Weak Turbulent Model for Swell Evolution, European Journal of Fluid Mechanics/B, 2007, 27, 361-387.

Resio, D.T. and J.J. Westerink: 2008, Modeling the Physics of Hurricane Storm Surges Physics Today, September, 33-38.

Irish, J.L., Resio, D.T., and J.J. Ratcliff, 2008: The influence of storm size on hurricane surge, J. Phys. Oceanogr., 38 (11), 2003-2013.

Resio, D.T. and W. Perrie, A two-scale approximation for nonlinear energy fluxes in a wind wave spectrum Part I , J. Phys. Oceanogr. 2008., Volume 38 (11), 2801-2816.

Onorato, M., Osborne, A. R., Janssen, P. A. E. M. & Resio, D.: 2009, Four-wave resonant interactions in the classical quadratic Boussinesq equations, J. Fluid Mech, 618 , 263-277.

Perrie, W. and D.T. Resio, A two-scale approximation for nonlinear energy fluxes in a wind wave spectrum Part II , accepted for publication in J. Phys. Oceanogr. 2008.

Resio, D.T., Irish, J.L., and M.A. Cialone, 2008: A surge response function approach to coastal hazard assessment: Part 1, Basic Concepts, accepted for publication J. Natural Hazards.

Irish, J.L., D.T. Resio, and M.A. Cialone, 2008: A surge response function approach to coastal hazard assessment: Part 2, Quantification of spatial attributes of response functions, accepted for publication J. Natural Hazards.

APPENDIX B

PARTIAL LIST OF COULWAVE PUBLICATIONS

(1) Lynett, P., Liu, P. L.-F., Losada, I., and Vidal, C., "Solitary Wave Interaction with Porous Breakwaters," *Journal of Waterway, Port, Coastal, and Ocean Engineering (ASCE)*, v. 126(6), p. 314-322. 2000.

(2) Lynett, P., Wu, T.-R., and Liu, P. L.-F., "Modeling Wave Runup with Depth-Integrated Equations," *Coastal Engineering*, v. 46(2), p. 89-107. 2002.

(3) Lynett, P. and Liu, P. L.-F., "A Two-Dimensional, Depth-Integrated Model for Internal Wave Propagation," *Wave Motion*, v. 36, p. 221-240. 2002.

(4) Lynett, P. and Liu, P. L.-F., "A Numerical Study of Submarine Landslide Generated Waves and Runup," *Proc. Royal Society of London A*. v. 458, p. 2885-2910. 2002.

(5) Liu, P. L.-F., Lynett, P., and Synolakis, C.E., "Analytical Solutions for Forced Long Waves on a Sloping Beach," *Journal of Fluid Mechanics*, v. 478, p. 101-109. 2003.

(6) Cheung, K., Phadke, A., Wei, Y., Rojas, R., Douyere, Y., Martino, C., Houston, S., Liu, P. L.-F., Lynett, P., Dodd, N., Liao, S., and Nakazaki, E., "Modeling of Storm-induced Coastal Flooding for Emergency Management," *Ocean Engineering*, v. 30, p. 1353-1386. 2003.

(7) Lynett, P., Borrero, J., Liu, P. L.-F., and Synolakis, C.E., "Field Survey and Numerical Simulations: A Review of the 1998 Papua New Guinea Tsunami," *Pure and Applied Geophysics*, v.160, p. 2119-2146. 2003.

(8) Ryu, S., Kim, M.H., and Lynett, P., "Fully Nonlinear Wave-Current Interactions and Kinematics by a BEM-based Numerical Wave Tank," *Computational Mechanics*, v. 32, p. 336-346. 2003.

(9) Basterretxea, G., Orfila, A., Jordi, A., Casas, B., Lynett, P., Liu, P. L.-F., Duarte, C. M., and Tintoré, J., "Seasonal Dynamics of a Microtidal Pocket Beach with Posidonia Oceanica Seabeds (Mallorca, Spain)," *Journal of Coastal Research*, v. 20(4), p. 1155-1164. 2004.

(10) Lynett, P. and Liu, P. L.-F., "A Two-Layer Approach to Water Wave Modeling," *Proc. Royal Society of London A*. v. 460, p. 2637-2669. 2004.

(11) Lynett, P. and Liu, P. L.-F., "Linear Analysis of the Multi-Layer Model," *Coastal Engineering*, v. 51(6), p. 439-454. 2004.

(12) Hsiao, S.-C., Lynett, P.., Hwung, H.-H., and Liu, P. L.-F, "Numerical Simulations of Nonlinear Short Waves Using the Multi-Layer Model," *Journal of Engineering Mechanics* v.131(3), p. 231-243. 2005

.

(13) Lynett, P. and Liu, P. L.-F., "A Numerical Study of the Runup Generated by Three-Dimensional Landslides," *JGR-Oceans,* doi:10.1029/2004JC002443. 2005

(14) Korycansky, D. G. and Lynett, P., "Offshore Breaking of Impact Tsunami: the Van Dorn Effect Re-Visited," *Geophysical Research Letters,* v. 32, No. 10, 10.1029/2004GL021918. 2005

(15) Sitanggang, K. and Lynett, P., "Parallel Computation of a Highly Nonlinear Boussinesq Equation Model through Domain Decomposition" *International Journal for Numerical Methods in Fluids*, v. 49(1), p. 57-74. 2005

(16) Liu, P., Lynett, P., Fernando, J., Jaffe, B., Fritz, H., Higman, B., Synolakis, C., Morton, R., and Goff, J., "Observations of the International Tsunami Survey Team in Sri Lanka," *Science*. v. 308(5728), p. 1595, June 10, 2005.

(17) Lynett, P., "Nearshore Modeling Using High-Order Boussinesq Equations," *Journal of Waterway, Port, Coastal, and Ocean Engineering (ASCE),* v. 132(5), p. 348-357. 2006.

(18) Lynett, P., "Wave Breaking Velocity Effects in Depth-Integrated Models," *Coastal Engineering*, v. 53, p. 325-333. 2006.

(19) Goff, J., Liu, P., Higman, B., Morton, R., Jaffe, B., Fernando, J., Lynett, P., Fritz, H., Synolakis, C., and Fernando, S., "Sri Lanka Field Survey after the December 2004 Indian Ocean Tsunami," *EERI Spectra*., v. 22(S3), p. 155-172. 2006

(20) Lynett, P., "The Effect of a Shallow Water Obstruction on Long Wave Runup and Overland Flow Velocity," in press, *Journal of Waterway, Port, Coastal, and Ocean Engineering (ASCE)*.

(21) Korycansky, D. G. and Lynett, P., "Runup from Impact Tsunami," in press *Geophysical Journal International*.