HARC

ANALYSIS OF THE HURRICANE IKE STORM SURGE AND WAVES

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EXECUTIVE SUMMARY

The Coastal Impact Assistance Program (CIAP) funded HARC to coordinate the data collection, analysis, and strategy evaluation aimed at developing recommendations that would promote the creation of offshore breakwater islands to reduce damage from hurricane storm surge and wave action. The project goals were:

- Develop models of the potential for several types of near-shore ecologies to mitigate storm surge and wave damage.
- Conduct a survey that elucidates public preferences of strategies of storm surge and wave damage mitigation.
- Produce a report combining the scientific models of mitigation of storm surge and wave damage and public opinion on mitigation strategies.

The project objectives were to:

- Produce models of storm surge and wave action along Harris County shoreline with and without natural mitigation features.
- Complete and summarize a statistically valid public opinion survey on storm surge and wave damage mitigation strategies.
- Complete and deliver a final report on the efficacy of storm surge and wave damage mitigation strategies using natural and engineered features and the public opinion about these options.

CIAP funds were used to support the Institute for Computational Engineering and Sciences at University of Texas at Austin and the Department of Civil Engineering at Texas A&M University to provide storm surge and wave modeling. Survey work was conducted by the Center for Texas Beaches and Shores and Institute for Sustainable Coastal Communities at Texas A&M University-Galveston to assess public preferences. This report presents a review of existing information, observed storm surge levels and damage during Hurricane Ike, a summary of the modeled storm impacts with and without breakwaters, results of the stakeholder survey on strategy preferences, and recommendations on efficacy and acceptability of using offshore barrier islands to reduce vulnerability.

Of the 17 different breakwater configurations modeled with the SWAN model, only Configurations 3 and 4 showed a reduction in water height. These two configurations were then modeled for several different breakwater heights using the SWAN+ADCIRC model. The most significant results were obtained for Configuration 4, levee height 5.5 m (18 ft); however, the maximum water elevation was not significantly reduced at any station location. The survey results indicated that respondents generally favored non-structural measures over structural measures, even though they believed that the non-structural methods were less effective. Based on the results of this research, we recommend additional study of how non-structural methods could reduce damage from storm surge and waves.

1.0 PROJECT DESCRIPTION

This Section describes the purpose of this research project, along with a summary of other related research in Galveston Bay.

1.1 Purpose

The purpose of this project was to conduct data collection, analysis and modeling for a study of the storm surge and wave impacts on land in Harris County around Galveston Bay due to Hurricane Ike in 2008 and effective ways to use breakwater islands to mitigate the effects. Analyzing the impact of Hurricane Ike represented an opportunity to isolate the effects of storm surge and wave action and develop policy options related to creation of systems for enhancement of coastal resilience. The project was coordinated and managed by HARC.

The wind and water impacts of Hurricane Ike had a substantial effect on people, structures, and natural resources around Galveston Bay. Storm surge typically causes flooding damage in the properties due to rising water at a relatively slow rate of 0.5 to 2 feet per hour; so it is not the main reason for the large scale destruction of structures on the coast. However, storm surge enables higher waves, which in turn cause high impact and sudden damage to structures. Waves entering the shallow water start to "feel the bottom", and become steeper and break. This breaking is the dissipation of the energy in the waves and can cause the destructive action during a hurricane through the battering effects of the water.

The Harris County Housing Authority conducted a survey, which concluded that Ike damaged more than 50% of the homes in the county. The hurricane left more than 18,000 residential units uninhabitable. The monetary loss for residential property in the county was estimated at $8.2 billion. About one third of the total cost of damage was caused by surge and waves. Harris County has more than 55% of its land classified as developed. The extent and cost of this natural disaster could provide justification for creation of engineered or natural systems that reduce storm surge and wave damage.

HARC developed this project to coordinate data collection, analysis, and strategy evaluation aimed at developing recommendations that would promote creation of effective systems to reduce damage from storm surge and wave action of hurricanes. Specifically, the effect of creating offshore breakwater islands to reduce some of the destructive force of the waves was investigated. These islands were not intended to eliminate the rising water from the surge, but to absorb the energy of the waves by forcing the waves to break offshore and then have to regenerate in a shorter distance between the breakwater island and the shoreline. The idea is that with the breakwaters closer to the shore the waves don't have time to fully develop on the landward side. The proposed islands would be a natural area/wildlife habitat, which would have sand and vegetation on the top and a more robust structure at the bottom to stand against the force of hurricane waves and surge. Should the top layer of sand and vegetation be washed away by a future hurricane's surge and waves, it would need to be replenished.

Preliminary SLOSH model runs were conducted by the Harris County Flood Control District (HCFCD) to assess the effect of a breakwater island along the coast of Harris County in reducing wave height. The HCFCD staff tested the distances of 1 mile and 5 miles off the coast for a range of wind speeds and Ike's wind directions. One-mile distance models showed higher reductions in wave heights than the 5 mile distance models. The approximate height of the modeled island was about 4 feet above mean sea level.

1.2 Other Relevant Research

This research on modeling effective ways to use breakwater islands to mitigate the effects of a storm is one of many studies on increasing the resiliency of the Texas Gulf Coast. The results of this study will provide valuable information for the on-going research efforts in the region. These studies include:

Gulf Coast Community Protection and Recovery District
In November 2008, Governor Rick Perry issued an Executive Order creating the Governor's Commission for Disaster Recovery and Renewal. Based on the commission's recommendation, Brazoria, Chambers, Galveston, Harris, Jefferson, and Orange Counties formed the Gulf Coast Community Protection and Recovery District (GCCPRD) with the purpose of conducting studies and developing plans to alleviate damage from future storm events. In September 2013, the GCCPRD received a grant from the Texas General Land Office (GLO). The purpose of this grant was to study opportunities for storm surge and flooding related disaster preparedness along the upper Texas coast. The GCCPRD has been collecting and analyzing existing data, and collaborating with other organizations and universities conducting similar work, and finalized their Phase I Storm Surge Suppression Study Report on February 27, 2015. Phase 2 of the study will focus on further evaluating and developing the initial proposed alternatives. Phase 2 is scheduled to be completed in April 2016. The final Phase 3 report is scheduled to be completed in June 2016. (GCCPRD, 2015)

Severe Storm Prediction, Education and Evacuation from Disasters Center
The Severe Storm Prediction, Education and Evacuation from Disasters (SSPEED) Center at Rice University was established in 2007, to address severe storm prediction and its impact on the Gulf Coast area. Initially, the Center focused on an upper- Galveston Bay structure that was frequently referred to as the "Centennial Gate". The SSPEED Center at Rice is currently engaged in a study to investigate and develop a potential regional surge protection system for the Houston-Galveston area, known as H-GAPS (Houston-Galveston Area Protection System). To

date, the work has involved the evaluation of Baseline Conditions and a variety of scenarios for reducing surge flooding in the Galveston Bay area. The SSPEED Center has begun evaluating three gate option strategies for the bay, and will continue to refine and optimize these options over the next two years. (SSPEED Center, 2015) These current strategies are more focused on mid-Galveston Bay.

Texas A&M University at Galveston
Texas A&M University at Galveston (TAMU-Galveston) is conducting research into lower Galveston Bay structural improvements that could provide protection from major storm surges. These improvements, often referred to as the "Ike Dike" or "Coastal Spine," would extend the existing Galveston Seawall along the rest of Galveston Island and along the Bolivar Peninsula, with a 17ft high revetment near the beach or raising the coastal highways. The plan also involves evaluating the addition of flood gates at Bolivar Roads, the entrance to the Houston, Texas City, and Galveston ship channels, and at San Luis pass. The Interim Design Report for the project was completed June 10, 2015 (Jonkman et. al.) A Draft Interim Report - Ike Dike Concept for Reducing Hurricane Storm Surge in the Houston-Galveston Region was submitted in September 2015 (Ebersole et al.) The team has also completed a draft Report on the Economic Impacts of Coastal Protection from Surge-Induced Flood Damage (Davlasheridze, nd)

Texas General Land Office and U.S. Army Corps of Engineers
The US Army Corps of Engineers (USACOE) produced a Coastal Risk Reduction and Resilience report in July 2013. In August 2014 the USACOE conducted a series of workshops and public scoping meetings to gather ideas for addressing coastal storm damage risk management and ecosystem restoration on the Texas coast. On August 31, 2015, The Texas General Land Office and the U.S. Army Corps of Engineers announced that they signed an agreement to begin developing a Coastal Texas Protection and Restoration Feasibility Study. The study will investigate the feasibility of projects for flood reduction, hurricane and storm damage mitigation and ecosystem restoration along the entire Texas coast. This study will evaluate coastal barrier and inland barriers, such as the Ike Dike and Centennial Gate as well as other structural and nonstructural alternatives to reduce coastal storm surge.

2.0 METHODS

This section presents a summary of the methods used by TAMU- College Station to complete the SWAN modeling, University of Texas – Austin (UT-Austin) to complete the SWAN+ADCIRC modeling, TAMU – Galveston to complete the survey, and by HARC for stakeholder engagement. The complete report on the SWAN model is included as Appendix A, the complete report on the SWAN+ADCIRC model is included as Appendix B, and the complete report on the survey is included as Appendix C.

2.1 SWAN Modeling

For this project, initially we proposed to run the Sea, Lake and Overland Surges from Hurricanes SLOSH model for quick and effective results to test a range of scenarios with different island height and distances from the coast to determine the optimal combination of scenarios. The SLOSH model is a computerized numerical model developed by the National Weather Service to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. HCFCD had completed some initial SLOSH modeling and stated that a more comprehensive investigation using a sophisticated numerical wave and storm surge model was needed. Therefore, TAMU-College Station used a numerical wave model, Simulating Waves Nearshore (SWAN) model (Booij et al. 1999), to simulate the generation and propagation of wave energy due to forcing by wind.

The SWAN model is a spectral wave propagation model which simulates:

- Wave energy generation by wind
- Wave energy propagation
- Wave energy dissipation by bottom friction, whitecapping and depth-limited wave breaking
- Wave energy redistribution by nonlinear interactions

This numerical spectral wave model does not propagate individual waves over the ocean, it propagates wave energy spectra over the domain without regard to the phase of the individual waves. This phase-averaged model is the only way wind-wave generation can be simulated on a realistic spatial scale. In this “phase-averaged” approach neither wave diffraction, nor nearshore nonlinear interaction, is well represented. However, the lack of representation of these effects was not anticipated to have a noticeable impact. Like all models of its type, the SWAN model will output predicted significant wave heights (a standard statistical measure of wave height in a random sea), peak period (the period of the wave with the predominant fraction of energy), peak direction, and other statistical parameters derivable from wave spectra.

The researchers at TAMU-College Station evaluated a series of breakwater island systems to test their ability to reduce the near shore wave heights on the Harris County side of the Galveston Bay. Wind fields representative of those from Hurricane Ike were run through a wave prediction model to generate maximum storm wave heights from Texas City Dike to Baytown. These scenarios were generated first without barriers, and then with a variety of barrier configurations.

The SWAN model was set up in four domains of increasing grid resolution and decreasing extents, starting from a coarse resolution model of the entire Gulf of Mexico and ending at a high resolution model of Galveston Bay and Trinity Bay. This allowed the effect of both local wind generation and incoming swell from remote generation areas to be included.

Environmental input to the wave model includes:

- Wind velocities, which are assumed to be at an elevation of 10m above sea level
- Bathymetry (underwater topography)
- Water level information (needed if tides or surge are important)
- Wave information along the model boundaries (if relevant)
- Current velocities (if relevant / available)

Wind Velocities: Two steps in wind processing were required:

1) The hurricane winds needed to be interpolated to fill in missing data in time. For each data gap, the wind velocities were interpolated to the gap in time using linear interpolation. The positions of the wind vectors were then interpolated in space to the intermediate point. This has the effect of simply translating the interpolated windfield (with structure intact) to the intermediate position.

2) The hurricane winds then needed to be gridded to the model grid resolution. The researcher used a bathymetric grid for the Gulf of Mexico that extended from 98 deg. W to 80 deg. W and 18 deg. N to 30 deg. N. The grid spacing is 2' X 2', which is about 3.39km longitude by 3.7km latitude. The computational grid matches the bathymetric grid. The hurricane winds were then interpolated to this larger grid, with zero values populating the areas of the grid outside the hurricane. These wind files, one for each three-hour time frame, were then concatenated for input to the model.

Time: Based on the time of transit of Ike through the Gulf, the researchers used 9/9/2008 0730UTC to 9/13/2008 1030UTC as the time of simulation (from when Ike entered the Gulf over Cuba to when it made landfall on the north shore of Galveston Bay).

Bathymetry: Bathymetric data came from the Design-A-Grid utility at the National Geophysical Data Center. For the Gulf, the ETOPO2 global relief grid was used. The ETOPO2 global relief grid has a resolution of 2' x 2'. For the coastal area in the northern Gulf, the U.S. Coastal Relief Model dataset was used. It has a resolution of 3"x3" (very roughly 100m) and can resolve Galveston Bay.

Water level information: The only data for the recorded surge available was that recorded by the US Geological Survey. The data exists only along the open coastline and within the bay, and is of varying quality. For this modeling effort, a maximum surge value was averaged across all gages bordering the bay, and was set at 3.66m.This level was set to be constant over the entire course of the wave runs in the bay.

Time-Step: Initially the model was tested with time steps of 1-minute and 5 minutes with no appreciable differences in results. Therefore, the time step for the model was 5 minutes. The spectral resolution involved a logarithmic spacing of wave frequencies between 0.06Hz to 1Hz, and 72 directions were run (5 degree resolution).

Barrier Placement and Configurations: There were no constraints given to the sizing or placement of the breakwater islands. In the interest of limiting the parameter space over which an optimum configuration could be found, it was decided to limit the barriers to two different types:

1) Long continuous breakwater of arbitrary length
2) Island segments 1.5km in length

The length of 1.5km was estimated from the breakwater layout from the Harris County Flood Control District. The various breakwater configurations here are shown in the report included as Appendix A. In general, the following guided the barrier placements:

- Those close to the western shoreline of Galveston Bay were placed to provide direct protection as a “last line of defense”. These were placed roughly 1.2km from the shoreline.
- Those located about 2.4km away from the shoreline were intended to intercept the wave before wide-scale breaking (and the resulting wave-induced setup) occurred.
- Those close to the ship channel were placed there to inhibit wave growth at the shoreline by reducing the fetch (the area over which the wind blows to generate waves)
- Those in Trinity Bay were placed there to inhibit the fetch even further, particularly from the easterly winds at the arrival of the hurricane.
- Those located at the northern end of the channel are intended to protect areas such as Baytown and Morgan’s Point.
- Some configurations consisted of modifications and combinations of other configurations, or of barriers added to other configurations.

In total, 17 different barrier configurations were modeled using the SWAN model.

2.2 SWAN+ADCIRC Modeling

Once the SWAN model determined the optimal configuration, the barrier locations were given to the UT–Austin Institute for Computational Engineering and Sciences for SWAN+ADvanced CIRCulation (ADCIRC) modeling. The initial SWAN modeling simulated the generation and propagation of wave energy due to forcing by wind, but did not incorporate a storm surge model. The UT researchers ran a fully coupled wave-surge model to generate a more comprehensive picture of the effect of breakwaters on the Harris County shoreline using the SWAN+ADCIRC wave-circulation simulator. UT researchers developed finite element grids and input files suitable for executing SWAN+ADCIRC under Hurricane Ike conditions. In particular, UT researchers modified existing high resolution models of the upper Texas coast to incorporate breakwater islands. They tested SWAN+ADCIRC on this model on the two optimal barrier island configurations, with conditions from Hurricane Ike. The researchers modeled both barrier configurations at three different heights: 1.2m (4ft), 3.0m (10ft), and 5.5m (18ft).

The ADCIRC storm surge model solves the depth-averaged barotropic form of the shallow water equations for water levels and momentum. Since the fidelity of a storm surge model significantly depends on the use of a suitably large physical region, the computational domain used included the western North Atlantic Ocean and entire Gulf of Mexico. The unstructured finite element mesh consisted of 1,846,542 nodes, with fine scale resolution incorporating a significant amount of detail around Galveston. The mesh spacing of this grid was approximately 1km on the continental shelf, 200m in the wave-breaking zones and inland, and 50m or less in the fine-scale channels and distributaries, down to a minimum 20m nearshore.

2.3 Survey

In order to assess public preferences on alternative mitigation strategies including engineering versus natural solutions, shoreline versus near-shore alternatives and acceptance of the proposed breakwater island concept, the TAMU-Galveston Center for Texas Beaches and Shores conducted a survey of residents of Harris County.

A mail survey was sent to 2,000 residents living in single-family homes during spring 2014, based on a stratified random sample. Stratification was based on distance to the coastline in five one-mile bands. Residents were asked to provide input on seven structural (breakwaters; groins and jetties; levees and dikes; seawalls and bulkheads; revetments; flood gates; and artificial reefs) and six non-structural (sand dunes; floating islands; wetlands; buffers and setbacks; oyster reefs; and sea grass beds) techniques that could possibly reduce wave based damage. Survey administration followed the Dillman technique, which features multiple waves of mailed surveys plus reminder cards (Dillman, 2009).

Respondents were asked to rate each technique using a 5-point Likert scale, where 1 = not at all, 2 = small extent, 3 = moderate extent, 4 = great extent, 5 = very great extent. The techniques were rated on the following categories.

- protect persons effectively,
- protect property effectively,
- useful for purposes other than flood protection,
- cost,
- politically feasibility
- effort required,
- level of cooperation from other communities required,
- something respondent favors being installed.

2.4 Stakeholder Input

Finally, HARC met with stakeholders to obtain their input on the results of model runs and public survey. HARC initially planned on presenting the results to stakeholders in the community that are responsible for disaster management. However, based on the results of the research, the stakeholder makeup was reevaluated and HARC worked with HCFDC and the Galveston Bay Estuary Program Research and Monitoring Subcommittee to present the results of the research and solicit feedback on next steps.

3.0 RESULTS

This section presents the results of the modeling and surveying tasks, and the input received from stakeholders. The complete report on the SWAN model is included as Appendix A, the complete report on the SWAN+ADCIRC model is included as Appendix B, and the complete report on the survey is included as Appendix C.

3.1 SWAN Modeling Results

A total of 17 different barrier configurations within Galveston Bay were evaluated. The following is a summary of the results of the analysis of wave height ratios at output points for the 17 configurations:

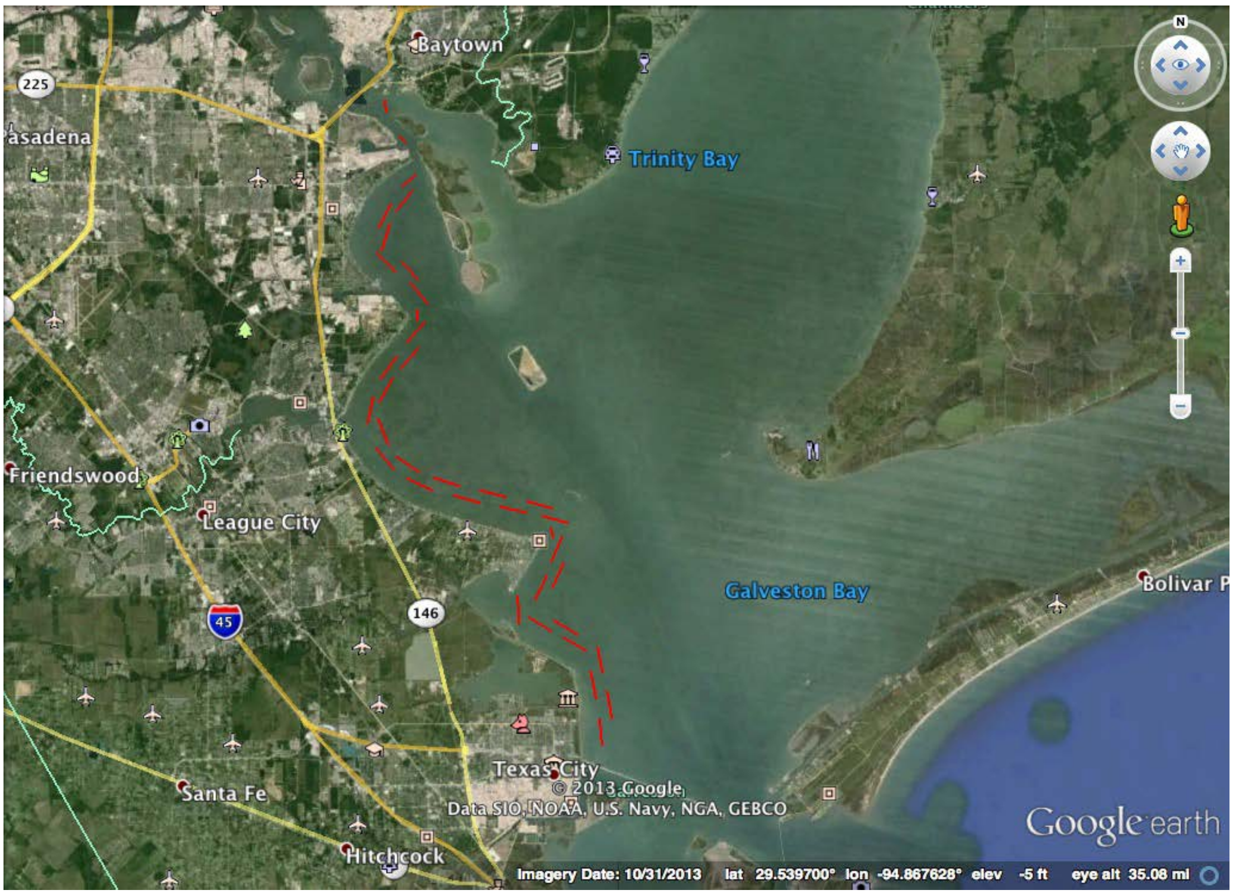
Statistic	Result
Configuration with the lowest wave height ratio averaged over all output points	Configuration 4 (0.89)
Configurations with average wave height ratio of 0.9 or less across all output points	Configurations 3, 4, 5, 6, 9, 11, 12, 13, 16
Lowest ratio of any configuration at any point	0.71 (Point 8, Configuration 4)
Configuration with the highest number of minimum wave height ratios over all output points	Configuration 4 (15 output points which had the minimum wave height ratio among all configurations)
Configurations with 10 or more output points with minimum wave height ratios	Configurations 4, 5, 11

Based on the modeling, the TAMU-College Station team determined that:

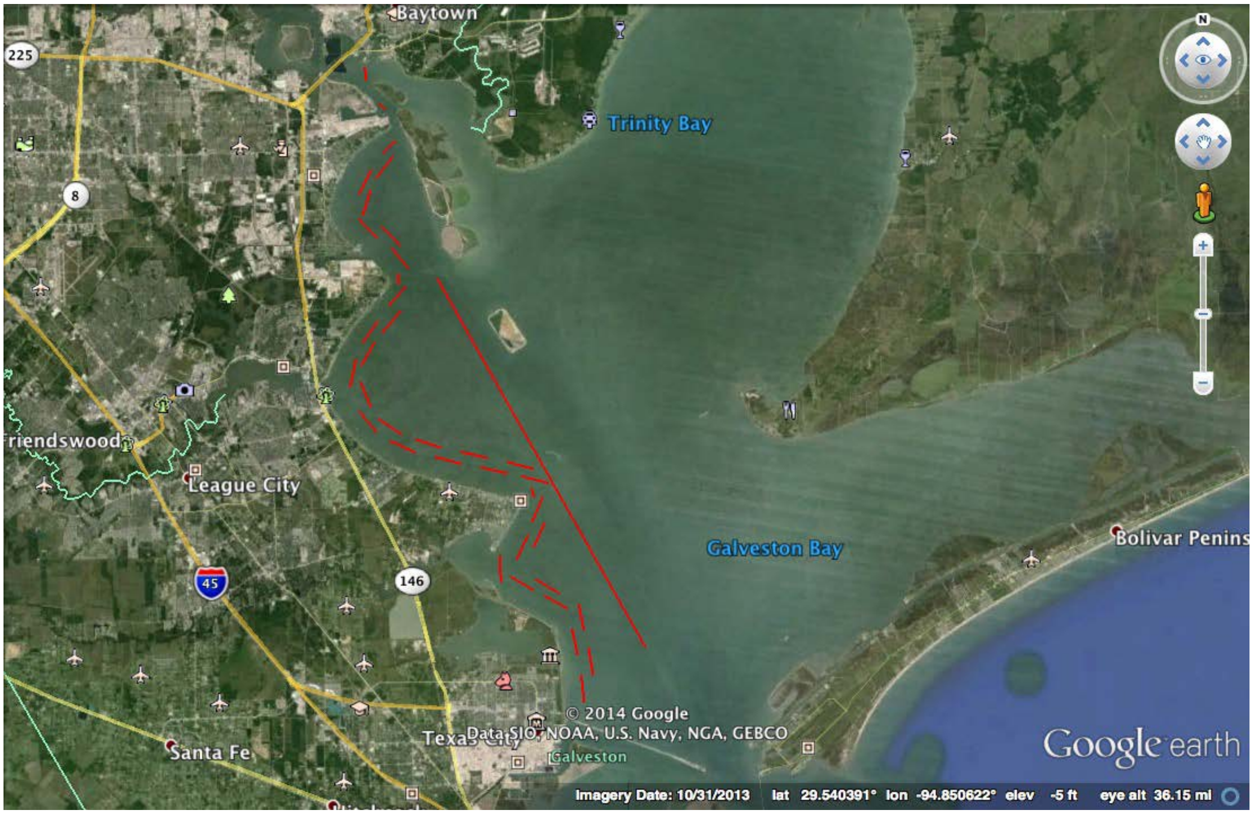
- All configurations that perform the well at reducing the maximum wave heights along the west coast of Galveston Bay include Configuration 3 as part of the overall design.

- The performance of Configuration 3 can be enhanced by the addition of barriers along the ship channel.
- The overall "best" wave attenuator is Configuration 4, but might not be the most convenient to construct, depending on whether long continuous structures are desirable.

Additionally, the model indicated that the maximum wave height ratio near the Baytown area was either unaffected or increased with barriers. This is likely due to wave energy generated by easterly winds being reflected off the barriers and back toward the shoreline. The amplification, however, is at most 8% of the maximum wave height without the barriers.



Configuration 3



Configuration 4

3.2 SWAN+ADCIRC Modeling Results

The UT-Austin team modeled TAMU-College Station breakwater Configurations 3 and 4 using breakwater heights of 1.2m (4ft), 3.0m (10ft) and 5.5m (18ft) above mean sea level.. Only the 18 ft. levee height with Configuration 4 showed an observable effect. With Configuration 4 at an 18 foot levee height, the modeling indicated some disruption of the water elevation across the long levee east of the shipping channel; this was not as obvious near the system of shorter levees. A total of 24 station locations were selected by HARC to study that range from the Texas City dike (Station 1) to Baytown (Station 24). Hydrographs for these stations are provided in the UT-Austin report included as Appendix B. The results shown in Table 1 indicate that the configuration does little to block the storm surge at these recording stations. Stations 2-13 show the most difference between the original hydrograph and that of Configuration 4, but the difference is not very significant.

Table 1. Maximum water surface elevation above mean sea level (in meters) for Configuration 4 levee height 5.5m (18ft), and for no barriers at 24 specified station points. (UT, 2015)

	Maximum water surface elevation above mean sea level (m)		
	Configuration 4	No Barriers	Difference (with-without)
1	3.91524E+00	3.92866E+00	-1.34200E-02
2	3.82003E+00	3.74197E+00	7.80600E-02
3	3.77535E+00	3.64406E+00	1.31290E-01
4	3.72653E+00	3.62945E+00	9.70800E-02
5	3.73731E+00	3.61818E+00	1.19130E-01
6	3.76532E+00	3.60791E+00	1.57410E-01
7	3.78277E+00	3.58257E+00	2.00200E-01
8	3.43053E+00	3.38731E+00	4.32200E-02
9	3.42917E+00	3.41709E+00	1.20800E-02
10	3.41992E+00	3.44034E+00	-2.04200E-02
11	3.41445E+00	3.45987E+00	-4.54200E-02
12	3.45689E+00	3.52566E+00	-6.87700E-02
13	3.50357E+00	3.54129E+00	-3.77200E-02
14	3.68994E+00	3.72371E+00	-3.37700E-02
15	3.71462E+00	3.74246E+00	-2.78400E-02
16	3.73879E+00	3.76258E+00	-2.37900E-02
17	3.75492E+00	3.77605E+00	-2.11300E-02
18	3.84350E+00	3.85582E+00	-1.23200E-02
19	3.95245E+00	3.96266E+00	-1.02100E-02
20	3.99243E+00	4.01247E+00	-2.00400E-02
21	4.05120E+00	4.07063E+00	-1.94300E-02
22	3.99616E+00	4.01635E+00	-2.01900E-02
23	4.02637E+00	4.03904E+00	-1.26700E-02
24	3.99526E+00	4.01075E+00	-1.54900E-02

The SWAN output of significant wave height (SWH) over the course of the simulations indicated the most distinct difference between the original Ike wave field without barriers and that of Configuration 4 is observed in the graphs of locations 2-4 near Texas City and locations 7-14 between San Leon and LaPorte. The maximum SWH is recorded in Table 2 as well as the ratio of wave height with to height without barriers. The most significant ratio is 0.41 at stations 3 and 8 in the southwest portion of Galveston Bay. Stations 19 – 21 had ratios greater than 1 showing no decrease in wave height near Baytown. Given the geographic location of these stations, such results are not surprising.

Table 2. Maximum significant wave height (in meters) for Configuration 4 levee height 5.4864m (18ft), and for no barriers at 24 specified station points, as well as the ratio of with barriers to without barriers.

	Maximum significant wave height (m)		
	Configuration 4	No Barriers	Ratio of with barriers to without barriers
1	1.609298E+00	1.664267E+00	9.66971E-01
2	9.573652E-01	1.977385E+00	4.84157E-01
3	8.451396E-01	2.047307E+00	4.12805E-01
4	1.088541E+00	1.590094E+00	6.84577E-01
5	9.191273E-01	1.066513E+00	8.61806E-01
6	8.267915E-01	8.613589E-01	9.59869E-01
7	9.710316E-01	1.764879E+00	5.50197E-01
8	8.249397E-01	2.006334E+00	4.11168E-01
9	8.471988E-01	2.009796E+00	4.21535E-01
10	1.029994E+00	1.783201E+00	5.77609E-01
11	9.326947E-01	1.470676E+00	6.34195E-01
12	8.596856E-01	1.311125E+00	6.55686E-01
13	1.211426E+00	1.720116E+00	7.04270E-01
14	1.031927E+00	1.278517E+00	8.07128E-01
15	1.076158E+00	1.172429E+00	9.17888E-01
16	9.524975E-01	1.051157E+00	9.06142E-01
17	8.617603E-01	9.380400E-01	9.18682E-01
18	9.628950E-01	1.298390E+00	7.41607E-01
19	5.627212E-01	5.555414E-01	1.01292E+00
20	6.794362E-01	6.393097E-01	1.06277E+00
21	6.458584E-01	6.435456E-01	1.00359E+00
22	6.007301E-01	7.019267E-01	8.55830E-01
23	1.293464E+00	1.345137E+00	9.61586E-01
24	1.414585E+00	1.420015E+00	9.96176E-01

As previously stated, the most significant results were obtained for the Configuration 4, levee height 5.5m (18ft), system. Additionally, at locations near the Baytown area (points 22-24), the wave height is either unaffected by the addition of the levee system, or else slightly elevated. Because the maximum water elevation is not significantly reduced at any station location, UT-Austin did not recommend incorporating this system of levees as a storm surge attenuation technique.

3.3 Public survey on mitigation preferences

Overall, the response rate for the survey was 7.35%; out of 2,000 surveys mailed, the team received 147 responses. The average age of respondents was 59 years old and most had lived in their homes for approximately 19 years.

Overall, structural solutions for flood mitigation are fairly well tolerated among respondents. However, the results of the survey show a strong dichotomy between techniques respondents think are effective and those they favor. For example, techniques including dikes, seawalls, and floodgates are viewed as very effective in protecting people and property, but responses are significantly lower for favoring their installation. The data indicate that the perceived high cost of implementing these techniques is an impediment to public support.

In general, respondents favor non-structural more than structural surge mitigation techniques, particularly wetlands, sand dunes, and development setbacks. However, the perception is that non-structural mitigation is less effective than structural techniques in protecting people and property over the long term. Perceived cost for implementing these strategies is significantly lower than for structural approaches.

Respondents felt most strongly about a flood-reduction program that involves a mixture of both structural and non-structural techniques. Results indicate that residents support a multi-faceted approach to mitigating storm impacts that includes multiple approaches working synergistically to facilitate more resilient local communities. In fact, this item received one of the highest levels of support among all items in the survey.

Finally, individual solutions for reducing the adverse impacts of wave-based flooding, such as dry and wet-proofing did not receive strong support despite their potential effectiveness. The noted high cost of these techniques would have to be borne by the homeowner, limiting their attractiveness as a viable set of options.

3.4 Stakeholder Meetings

A meeting was held with staff from the Harris County Flood Control district to discuss the results of the research and determine how to best communicate the results. Because of the nature of the results, with the modeled structures providing little effect, reaching out to emergency managers or the public was not appropriate. Instead, Harris County Flood Control indicated that the modeling might provide useful information for other resiliency planning discussions, such as those discussed in Section 1.2.

On September 9, 2015, HARC presented the results of the research to the Galveston Bay Estuary Program's Environmental Monitoring and Research Committee. This committee provided a cross-section of stakeholders involved in management and planning for Galveston Bay. Overall the group noted favorably the public's broad support for non-structural features. There was also discussion of the public's perception that these non-structural features are not as effective as structural features. This is in contrast to communication subcommittee members have received from contacts in Louisiana. The modeling results will help these stakeholders and their colleagues communicate to the public that not all structural interventions are more effective than non-structural interventions, and natural buffers, setbacks, and building codes might be useful.

4.0 CONCLUSIONS

The results of the modeling indicate that incorporating a system of levees in Galveston Bay as a storm surge attenuation technique would not be effective. In addition, survey respondents favor non-structural more than structural surge mitigation techniques, particularly wetlands, sand dunes, and development setbacks. Some of the highest support among options in the survey was for a multi-faceted approach to mitigating storm impacts that includes using several techniques working synergistically to facilitate more resilient local communities.

> *"Due to the complex nature of the storm surge in Galveston Bay (hurricane induced surge on the coast combined with local wind set up in the bay) it is expected that an optimal strategy would likely include multiple lines of defense, including structural and non-structural interventions." (Jonkman et al, 2015)*

5.0 NEXT STEPS

Based on these results, additional modeling of the effectiveness of non-structural techniques, should be performed to provide useful input to the other studies in the area described in Section 1.2 that are more focused on structural solutions. This modeling could build upon previous studies such as:

- Shepard et al (2011), conducted a meta-analysis of the protective role of coastal marshes. Their results indicated that salt marshes have value for coastal hazard mitigation and climate change adaptation, but the magnitude of this value is not completely understood.

- Barbier et al (2013), combined hydrodynamic analysis of simulated hurricane storm surges and economic valuation of expected property damages. Their research indicated that the presence of vegetated coastal marshes had a demonstrable effect on reducing storm surge levels in southeast Louisiana. Simulations showed that surge levels declined with wetland continuity and vegetation roughness.

- Sigren et al (2014) conducted research at Texas A&M Galveston on the role of vegetation in coastal dune resilience. Restored vegetation is likely to act as a stabilizing agent in dune systems; however, there was a lack of scientific data on the impact of plants on dune erosion and protective capabilities during storms. Their pilot wave flume experiments suggested that plants have great potential to reduce dune erosion under wave and surge attack, and recommended additional modeling to optimize the protective capabilities of restored dunes.

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