

# Methodology for Risk Assessment for Exposure to Hurricane Conditions

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## Abstract

An analysis of potential flooding by storm surge and wave run-up and overtopping can be used to evaluate protection afforded by the existing storm protection system. The analysis procedure can also be used to evaluate various protection alternatives for providing typhoon flood protection. To determine risk, the storm surges for both historical and hypothetical are compiled with tide conditions to represent high, slack and low water for neap, spring and mid range tides to use with the statistical procedure known as the Empirical Simulations Technique (EST). The EST uses the historic and hypothetical events to generate a large population of life-cycle databases that are used to compute mean value maximum storm surge elevation frequency relationships. The frequency-of-occurrence relationship is determined for all relevant locations along the shoreline at appropriate locations to identify the effect using the Empirical Storm Simulation (EST). To assist with understanding the process, an example is presented for a study of storm surge analysis for Freeport, Texas. This location is in the Gulf of Mexico and is subject to hurricanes and other tropical storms that approach from the Atlantic Ocean.

**Keywords:** Storm Surge, Hurricane, Tidal verification, Empirical storm simulation, ADCIRC

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## 1. Introduction

A comprehensive analysis of storm damage potential requires numerical modeling of tides/storms, run-up on levees and frequency analyses of storm surge elevations associated with historical tropical and hypothetical storms to obtain extreme event storm surges and run-up values. Results of the analyses can then be used to evaluate storm protection afforded by the existing levee configuration or used to evaluate various levee alternatives for providing typhoon flood protection. The main computational resource for this study is the finite element numerical hydrodynamic model Advanced Circulation (ADCIRC), (Leutich et al., 1992). It is used to numerically simulate the propagation of tides and

storms at the study area. This task first requires development of a computational grid for the study area. The ADCIRC model then uses the computational grid to simulate tidal circulation and storm events. The model grid is verified by comparing model-generated tide time series with the corresponding time series reconstructed from existing harmonic analyses and on-site measurements of surface elevation. Storm event simulations are verified by comparing simulated results of water surface elevation with archived storm measurements. Once the model has been shown to be capable of reproducing historic events, all storms are simulated that significantly impacted the study area for which data are available. In order to insure that the most severe events have been included for all open coast stations, simulations include hypothetical events that could likely occur.

Following the numerical simulations for all the

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selected storms, the database of computed surges and tides are used as input for a statistical procedure known as the Empirical Simulation Technique (EST) which is described by Scheffner et al. (1999 and 2003). This procedure uses historic events to generate a large population of life-cycle databases that are post-processed to compute mean value maximum storm surge elevation frequency relationships with standard deviation error estimates. Frequency computations are made at many locations in the study area, often as close as every 100 m. These stations are located at points of interest within the domain and help in establishing the extreme event storm surges along the levee system. The study requires completion of the following five sequential modeling tasks: 1) grid development, 2) application and calibration of the ADCIRC model, 3) verification of model results for tides and storms, 4) application of the EST model and calculation of frequency relationships. To assist in understanding the procedures presented, an example is presented of the process that was recently used in the study of hurricane storm surge at Freeport, Texas, in the United States. This area is quite exposed to tropical storms that originate in the Atlantic Ocean, Caribbean Sea or the Gulf of Mexico.

## 2. Computational Grid

The modeling strategy for this example has been to define the entire Gulf of Mexico as the computational domain and to refine the region of interest using the significant grid flexibility offered by the finite elements and the ADCIRC codes. Using the entire Gulf as the pertinent domain is quite convenient from a variety of perspectives. Most important, two well-defined open ocean boundaries of limited extent can be used to specify the boundary forcing functions that define the interaction between the Atlantic Ocean and the Caribbean Sea with the Gulf. It would be convenient to extend the grid to capture all of the Caribbean Sea and the western Atlantic to minimize boundary effects.



Fig. 1. Satellite Image of Study Area (Freeport, Texas, US)

The open boundary across the Strait of Florida was selected to run from Cape Sable in Florida to Havana, Cuba. The second open boundary stretches just south of the Yucatan Strait. The resulting finite element grid consists of 28,266 nodes, 52,624 elements and is shown in Figure 2. Minimum node-to-node spacing in the study is approximately 50 m. The bathymetry for the computational domain is shown in Figure 3. The increased resolution of the study area is shown in Figure 4. This large domain approach to specification of boundary conditions virtually eliminates contamination of model results from poorly defined boundary conditions.

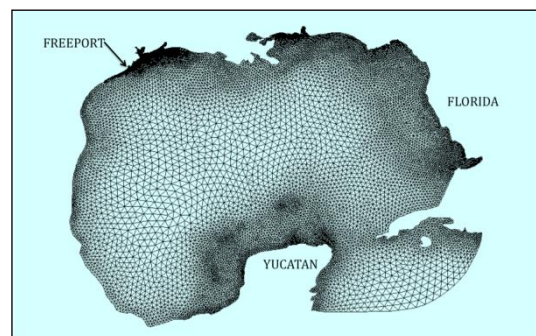


Fig. 2. Computational Domain

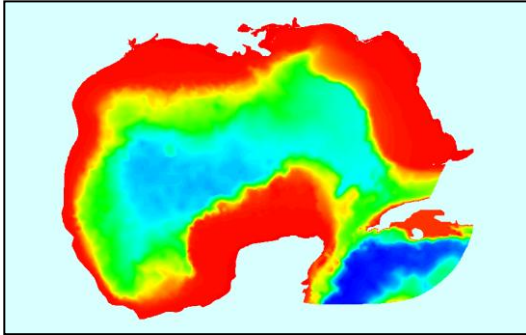


Fig. 3 Bathymetry in the Gulf of Mexico

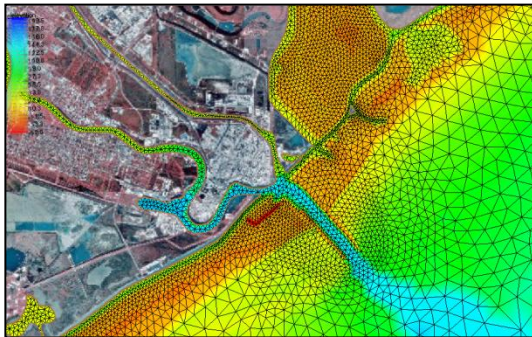


Fig. 4 Grid Resolution in the area of interest

The bathymetry in the Gulf of Mexico varies dramatically, as is illustrated in the Figure 3. Bathymetric data in most of the Gulf was obtained from the grid developed by Scheffner et al. (2003), GeoDas (a database developed by National Oceanic and Atmospheric Administration, NOAA), USACE surveys and surveys conducted by Texas A&M University in the area of interest. The grid was generated as a combination of finite element grid developed by Scheffner et al. (2003) and modified in the area of interest with details added. The grid in the area of interest was added using the SMS (Surface Modeling System) software package. To get a mesh/grid with density radiating from the center of the Freeport channel, size functions in SMS were used along with celerity and wavelength functions so that smaller elements are obtained closer to the shore to correctly model the area of interest. Note also that the grid extended over the barrier islands to allow inland flooding of normally dry land.

The model was “spun up” (started with progressively greater forcing such as tides or winds and pressure) from homogeneous initial conditions us-

ing a time ramp to avoid problems with short period gravity modes and vortex modes in the sub internal frequency range. A very smooth hyperbolic tangent ramp function, which acts over approximately one day, was applied to both boundary conditions and direct forcing functions. A 6-day spin-up was determined to be more than adequate for all conditions of interest. For simulation of the model, a time step of 6 sec was used for tidal propagation and a time step of 2 seconds was used for storm simulation in order to accommodate the strong gradients associated with strong winds in case of a storm. Using lower time steps resulted in oscillations and long term instabilities. The Courant number (The Courant Number constraint requires that the distance traveled by advection during one time step is not larger than one spatial increment ) based on wave celerity ranged from 0.0025 to 0.82. Time weighing factors of 0.35, 0.30 and 0.35 were used in the GWCE (Generalized Wave Continuity Equations). The parameter  $\theta$  was set equal to  $-0.005$  as this signals ADCIRC to use 0.005 in deep water and 0.02 in shallow water, so that a balance is set between the primitive continuity and wave equation portions of the GWCE equation.

Tidal water surface elevation data computed with the ADCIRC model were recorded at 15 locations for verification purposes. These locations are listed in Table1. Storm surge water surface elevations were archived for 12 locations within the area of interest for subsequent computation of frequency-of-occurrence relationships.

Table 1: List of stations used for tidal verification

S. No	Location	Longitude °	Latitude °
1	Corpus Christi	-97.38928	27.08113
2	Freeport Harbor	-95.34277	28.95019
3	Sabine Pass	-93.83873	29.68882
4	Galveston bay entrance south jetty	-94.69849	29.32304
5	Round Point Galveston Bay	-94.78059	29.31827
6	Galveston bay entrance	-94.70587	29.34739
7	Bolivar roads	-94.78388	29.34029
8	Galveston (channel) (2)	-94.78774	29.31305
9	Galveston Pleasure Pier	-94.78747	29.28495
10	Galveston channel	-94.80136	29.31203
11	Jamaica beach	-95.00899	29.19919
12	Morgan point	-94.9766	29.6756
13	Clear lake	-95.06118	29.55583

14 Lynchburg landing	-95.09607	29.77917
15 San Luis Pass	-95.12016	29.07968

### 3. ADCIRC Model

Water-surface elevations and currents for both tides and storm events are obtained from the large-domain long wave hydrodynamic model ADCIRC (Advanced Circulation model; Luettich et al., 1992). ADCIRC is a finite element (FEM) code that makes use of the Generalized Wave Continuity Equation (GWCE) for improved stability and efficiency over other FEM hydrodynamic codes. Included within the code are features that allow the user to include tidal and atmospheric forcing in the computations. Wind can be input in a variety of different formats and could be derived from any source that the user has available.

The 2-dimensional, Depth Integrated (2DDI) model formulation begins with the depth-averaged shallow-water equations for conservation of mass and momentum subject to incompressibility and hydrostatic pressure approximations. The Boussinesq approximation, where density is considered constant in all terms but the gravity term of the momentum equation, is also incorporated in the model. Using the standard quadratic parameterization for bottom stress and omitting baroclinic terms and lateral diffusion and dispersion, the following set of conservation statements in primitive, non-conservative form and expressed in a spherical coordinate system are incorporated in the model (Flather 1988; Kolar et al. 1994):

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left[ \frac{\partial UH}{\partial \lambda} + \frac{\partial(UV \cos \phi)}{\partial \phi} \right] = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + \frac{1}{R \cos \phi} U \frac{\partial U}{\partial \lambda} + \frac{1}{R} V \frac{\partial U}{\partial \phi} - \left[ \frac{\tan \phi}{R} U + f \right] V$$

$$= -\frac{1}{R \cos \phi} \frac{\partial}{\partial \lambda} \left[ \frac{P_s}{\rho_o} + g(\zeta - \eta) \right] + \frac{\tau_s \lambda}{\rho_o H} - \tau * V \quad (2)$$

$$\begin{aligned} & \frac{\partial V}{\partial t} + \frac{1}{R \cos \phi} U \frac{\partial V}{\partial \lambda} + \frac{1}{R} V \frac{\partial V}{\partial \phi} - \left[ \frac{\tan \phi}{R} U + f \right] V \\ & = -\frac{1}{R \cos \phi} \frac{\partial}{\partial \lambda} \left[ \frac{P_s}{\rho_o} + g(\zeta - \eta) \right] + \frac{\tau_s \phi}{\rho_o H} - \tau * V \end{aligned} \quad (3)$$

where  $\zeta$ : free surface elevation relative to the geoid,  $U, V$ : depth-averaged horizontal velocities,  $H = \zeta + h$ : total depth of water column,  $h$ : bathymetric depth relative to the geoid,  $f = 2 \Omega \sin \phi$ : Coriolis force,  $\Omega$ : angular speed of the Earth,  $\phi$ : latitude in degrees,  $\lambda$ : longitude in degrees,  $P_s$ : atmospheric pressure at the free surface,  $g$ : gravitational acceleration,  $\eta$ : effective Newtonian equilibrium tide potential,  $\rho_o$ : reference density of water,  $\alpha$ : effective Earth elasticity factor,  $\tau_{s\lambda}, \tau_{s\phi}$ : applied free-surface stress,  $\tau_* = C_f (U^2 + V^2)^{1/2} / H$ , bottom shear stress,  $C_f$ : bottom friction coefficient,  $R$ : radius of Earth,  $t$ : time.

In order to overcome general stability problems encountered when finite element models depend upon the direct solution of these primitive forms of the governing equations, the ADCIRC code was developed around the generalized wave continuity equation (GWCE). Combining a time-differentiated form of the momentum equations yields this form of the primitive equations. With the inclusion of a simple eddy viscosity model for closure, the GWCE in spherical coordinates takes the form:

$$\begin{aligned} & \frac{\partial^2 \zeta}{\partial t^2} + \tau_o \frac{\partial \zeta}{\partial t} - \frac{1}{R \cos \phi} \frac{\partial}{\partial \lambda} \left[ \frac{1}{R \cos \phi} \left( \frac{\partial(HUV)}{\partial \lambda} + \frac{\partial(HUV \cos \phi)}{\partial \phi} \right) - UVH \frac{\tan \phi}{R} \right] \\ & [-2\omega \sin \phi HV + \frac{H}{R \cos \phi} \frac{\partial}{\partial \lambda} (g(\zeta - \alpha\eta) + \frac{P_s}{\rho_o}) + \tau_o HU - \tau_o HU - \frac{\tau_s \lambda}{\rho_o}] \\ & - \frac{1}{R} \frac{\partial}{\partial \phi} \left[ \frac{1}{R \cos \phi} \left( \frac{\partial(HVV)}{\partial \lambda} + \frac{\partial(HVV \cos \phi)}{\partial \phi} \right) + UVH \frac{\tan \phi}{R} + 2\omega \sin \phi HU \right] \\ & - \frac{1}{R} \frac{\partial}{\partial \phi} \left[ \frac{H}{R} \frac{\partial}{\partial \lambda} (g(\zeta - \alpha\eta) + \frac{P_s}{\rho_o}) + (\tau_* - \tau_o) HV - \frac{\tau_s \phi}{\rho_o} \right] - \frac{\partial}{\partial t} \left[ \frac{VH}{R} \tan \phi \right] - \tau_o \left[ \frac{VH}{R} \tan \phi \right] = 0 \end{aligned} \quad (4)$$

The ADCIRC-2DDI model solves the GWCE (Equation 4) in conjunction with the primitive momentum equations given in Equations 2 and 3. The equations are solved using a FEM grid, made up of linear triangular elements (only three nodes per element). The model domain can be as extensive as an entire ocean basin, or more localized, as in the case of a small bay or estuary.

### 3.1 Tidal Propagation

Tidal potential forcing, which causes the normal observed periodic water level changes in large bodies of water, is included in ADCIRC. ADCIRC determines the magnitude of the tidal potential  $\eta$  in equation (4) at each grid node and each model time step by the relationship:

$$\eta(\lambda, \phi, t) = \sum_{j,n} B_{jn}(t_0) L_j(\phi) \cos \left[ \frac{2\pi(t-t_0)}{T_{jn}} + j\lambda + v_{jn}(t_0) \right] \quad (5)$$

where  $B_{jn}$ : tidal species (0: declinational, 1: diurnal, 2: semidiurnal),  $L_j$ : amplitude constant of the  $n$ th tidal constituent of species  $j$ ,  $T_{jn}$ : time dependent nodal factor,  $v_{jn}$ : time dependent astronomical argument,  $\phi$ : function for species  $j$  ( $\cos$ ,  $\sin$ ,  $\cos^2$ ),  $t_0$ : a reference time, usually the beginning time of simulation,  $T_{jn}$ : period of constituent  $n$  of species  $j$ .

The values of  $f$  and  $v_{jn}$  for the constituents used for the tidal potential computations are determined for the specific time that a model run begins using LeProvost database (Westerink et al., 1993). Note that tidal potential was not used during the simulation of tropical storms for the example of Freeport presented here. Tides were combined after the simulations during the frequency analysis.

### 3.2 Wind Forcing

In addition to the capability for tidal forcing within ADCIRC, there are provisions to input atmospheric and wind forcing information into the simulations. Several formats for the wind data are supported, including a fleet numeric and National Weather Service (NWS) wind file format. For this study, the Planetary Boundary Layer (PBL) model (Cardone et al. 1992) supplies the atmospheric forcing information. This model was developed to simulate typhoon generated wind fields using basic characteristics about a particular storm that can be easily retrieved from sources such as NWS archives of past typhoons, as well as forecast data for a currently active storm. This model simulates typhoon-generated wind and atmospheric pressure fields by solving the equations of horizontal motion that have been

vertically averaged through the depth of the planetary boundary layer. The PBL model requires input defining both the hourly location of the eye of the storm and a set of meteorological parameters defining the storm at various stages of development. These parameters include latitude and longitude of the eye of the storm, track direction and forward speed measured at the eye, radius to maximum wind, central and peripheral atmospheric pressures, and an estimate of the geostrophic wind speed and direction. A two-step process is used to generate wind fields for use by ADCIRC from the storm data. First, a program for the PBL model is used to determine the track of the storm as one our 'snapshots'. These snapshot data include the radius of maximum wind, which is approximated using a nomograph that incorporates the maximum wind speed and atmospheric pressure anomaly (Jelesnianski and Taylor, 1973). In the second step, the PBL model computes the wind field and pressure field of the typhoon.

## 4. Application of the Adcirc Model

Application of the ADCIRC model requires verification to ensure that grid resolution, bathymetry, and boundary conditions were acceptable to properly simulate conditions in the defined domain. For comparison of tidal simulations with observed tides, verification was accomplished for the Freeport example case using 8-constituents (M2, S2, N2, N1, K1, O1, Q1, and P1), as these constituents comprise most of the tidal energy, with tidal elevations calculated using software XTIDE which in turn uses published harmonic series. Verification for storm events is achieved by comparing computed surface elevation time series to surge data available from the National Ocean Survey (NOS) for the Pleasure Pier recording station.

### 4.1 Tidal Circulation

Tidal circulation is simulated within ADCIRC by specifying a surface elevation time series at the Florida Strait and just south of the Yucatan Strait as shown in the computational grid of Figure 2. This boundary condition specification is accomplished by reconstructing an 8-constituent

tidal elevation time series at each open water boundary node of the grid based on amplitudes and Greenwich epoch values obtained from a database incorporated in the SMS software also known as LeProvost database. Additionally, tidal potential terms are specified at each node of the computational grid. The ADCIRC model has an internal harmonic analysis option in which individual constituent amplitudes and epochs are computed at user specified locations during the tidal simulation. Verification of tidal circulation was made for the Freeport example by comparing both ADCIRC computed harmonic constituents and ADCIRC computed time series with existing constituent data and reconstructed time series at each of the 15 verification locations listed in Table 1. Comparisons of ADCIRC versus published Harmonic Analysis (HA) computed constituent amplitudes and Greenwich epochs (G) are shown in Table 2 for two locations. Because the Gulf of Mexico is a semi-enclosed body of water, approximately 10 to 15 days of spinup time are required for the tide to come to a dynamic equilibrium, i.e. when the tides are acceptably reproduced. The harmonic analysis used for the comparisons in Table 2 were based on a 43-day simulation of tides and during this time the harmonic analysis was computed for the 29-day (one lunar month) period of days 15 through 43. A period of comparative less wind activity was chosen to effectively compare the real-time data and ADCIRC simulated time-series. In order to demonstrate a degree of acceptability for the constituent comparisons shown in Table 2, a tidal elevation time series for days 15 through 43 is shown in Figures 5 and 6 at different recording stations. As shown, the comparisons are quite acceptable and fully adequate for the statistical generation of stage-frequency relationships.

Table 2. Tidal verification of ADCIRC along open coast for Freeport Example

Constituents	Galveston Pleasure Pier		Freeport Harbor	
	Amp - m	G - deg	Amp - m	G - deg
	Mod / HA	Mod / HA	Mod / HA	Mod / HA
K <sub>1</sub>	.162/. 197	33.2/42.6	.175/.188	18.7/26.6
O <sub>1</sub>	.162/. 187	20.8/32.1	.167/.178	13.2/15.9
P <sub>1</sub>	.051/. 056	14.2/18.5	.059/.065	17.1/21.6
Q <sub>1</sub>	.034/. 043	11.6/16.2	.037/.046	2.2/4.8

N <sub>2</sub>	.025/. 037	290.2/285.1	.024/.035	261.1/258.4
M <sub>2</sub>	.102/. 138	317.6/295.7	.092/.101	273.5/265.2
S <sub>2</sub>	.024/. 040	278.9/282.6	.033/.035	284.3/178.9
K <sub>2</sub>	.009/. 011	271.3/282.1	.014/.015	266.1/272.6

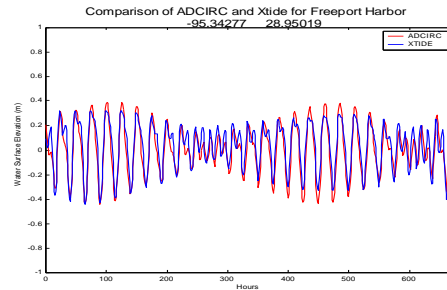


Fig. 5. Comparison of tides at Freeport Harbor

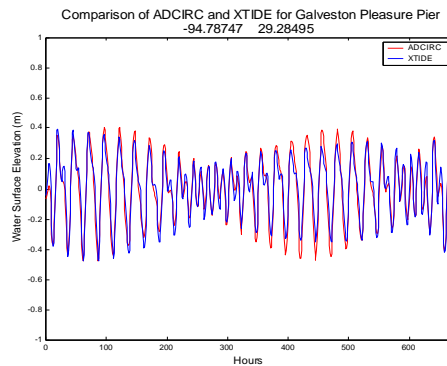


Fig. 6 Comparison of tides at Pleasure Pier

### 4.2 Tropical Storm Surge

The PBL model was used during this study and was coupled with ADCIRC in the form of a wind file, which can be input to the ADCIRC model to simulate wind affects of the storms for the area of interest. Peripheral atmospheric pressures were assumed equal to the standard atmospheric pressure of 1013 millibars (mb) and the geostrophic wind speeds were specified as 6 knots in the same direction as the moving eye of the storm. All additional data are computed from data contained in the National Oceanic and Atmospheric Administration’s (NOAA) Hurricane DATabase (HURDAT) of tropical storm events (Jarvinen et al., 1988). The typhoon Claudette (July 2003) was simulated by using track data from weather databases, which contain track information: latitude, longitude, time

along with minimum pressure and maximum wind. The goal of this component of the example study is to compute frequency-of-occurrence relationships for storm surge plus tide in the Freeport area. In order to develop these relationships, it is necessary to identify tropical storms that have historically impacted the study area. This was accomplished by making use of the tropical storm database (Scheffner, et al, 1994) that was generated through simulation of 134 historically based storm events along the east coast, Gulf of Mexico, and Caribbean Sea. The database uses the HURDAT database described above as input. For 486 discrete locations along the U.S. coast, peak storm surge values corresponding to storm events, which produced a surge of at least 0.305 m, were archived and indexed according to event, location, and surge magnitude. The Scheffner database was used to select 26 storm events for the present study beginning with the typhoon of 1886 and extending through Typhoon Claudette (2003). These events, shown in Table 3, represent the historical training set of storms.

18. #722 – Delia	9/1/1973	1
19. #809 – Chris	9/9/1982	1
20. #812 – Alicia	8/15/1983	3
21. #841 – Bonnie	6/23/1986	1
22. #867 – Chantal	7/30/1989	1
23. #874 – Jerry	10/12/1989	1
24. #923 – Dean	7/28/1995	1
25. #965 – Frances	9/8/1998	1
26. #1001 – Allison	6/5/2001	1
27. #1016 - Claudette	7/5/2003	1

This set of tropical storms is verified by comparing National Ocean Survey (NOS) measured tide gage records taken at Pleasure Pier and Freeport Harbor. These data are ideal for storm event verification effort as it allows calibration of the radius of maximum wind that is an important input to the PBL model to optimize the model for comparison of the set of storms for the area of interest. Due to spin-up time of 10-15 days required for tidal simulations, the decision was taken to compare storm surge elevations without tidal forcing. Therefore, surge only storm surge time-series were constructed by removing the astronomical tide from the raw NOS tide gage records, and the ADCIRC surge was computed without tidal forcing. For example, Figure 7 shows a time series of NOS data for Freeport for Typhoon Claudette (2003). As is evident from Figure 7, the storm surge is accurately captured; however, the tides are not accurately simulated due to spin-up time required for tidal simulation in the Gulf. In Figure 8, surge-only data is shown, which is computed by subtracting tide and pre-storm datum from the raw signal.

Table 3 Tropical storms set

HURDAT No./Name	Date of Storm	Category
1. #5 8/12/1886		2
2. #117	8/27/1900	4
3. #183	7/13/1909	4
4. #211	8/5/1915	4
5. #232	8/1/1918	2
6. #295	6/27/1929	1
7. #310	8/12/1932	4
8. #324	7/25/1933	1
9. #397	8/2/1940	1
10. #405	9/16/1941	1
11. #445	8/24/1945	4
12. #565 – Audrey	6/25/1957	4
13. #586 – Debra	7/23/1959	1
14. #602 – Carla	9/3/1961	5
15. #690 – Celia	7/31/1970	3
16. #703 – Edith	9/5/1971	5
17. #704 – Fern	9/3/1971	1

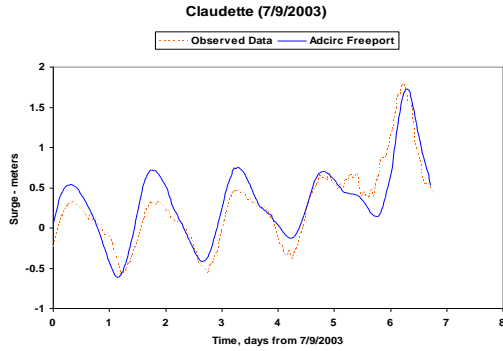


Fig. 7. Raw surface elevation data for Typhoon Claudette at Freeport Harbor

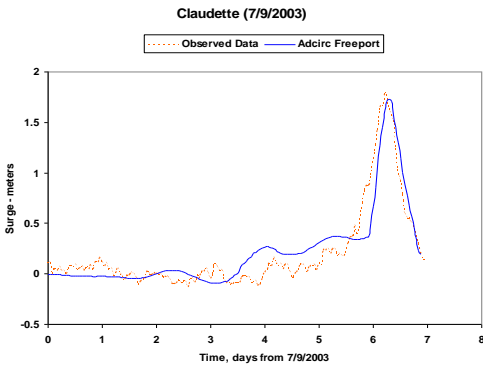


Fig. 8 Surge only surface elevation data for Typhoon Claudette

### 4.3 The Empirical Simulation Technique

The Empirical Simulation Technique (EST) is a procedure for simulating multiple life-cycle sequences of non-deterministic multi-parameter systems such as storm events and their corresponding environmental impacts. Another direction that can be taken is by the use of the Joint Probability Distribution method (JPM). Resio (2006) discusses the procedures for the JPM and the advantages. the sliding surface will then converge to zero when it satisfies the Lyapunov stability, as follows:

The descriptive characteristics of the storm event with respect to the specific location of interest are determined by the input parameters or input vectors. For tropical storms these input parameters are studied at the point when the eye of the typhoon is

closest to the station of interest. These vectors are defined as:

- Tidal phase during the event, with 1.0 corresponding to high water slack, 0.0 MSL at maximum ebb, -1.0 low water slack, these represent relative values that are defined for each station
- Radius of maximum wind for the typhoon in nautical miles.
- Minimum distance from the eye of the storm to the location of interest in nautical miles.
- Pressure at the typhoon eye in millibars (mb)
- Wind speed in the typhoon at the instant of eye hitting the coast, measured in knots.
- Direction of forward propagation of the eye of the typhoon

The maximum storm surge elevation reached at specified gauge locations is defined as the response vector of the storm at that location. The specified response vector for this study was determined by simulating the specific storm event via the ADCIRC hydrodynamic model using the computational domain shown in Figure 2.

In order to establish the training set of storms for the Freeport example, 27 historical events and 10 storm perturbations were used to produce a total of 37 events. Each of the 37 storms was simulated without tide to produce a set of surge-only responses at the stations. The storms are then assumed to have taken place at different phases of the astronomical tides: 1) high tide, 2) mean (MSL = 0.0) tide, and 3) low tide. It is further assumed that the storm could occur during the lunar cycles of: 1) spring tide, 2) between spring and neap, and 3) neap tide. Input vectors representing these phases of the tide are described above. This combination of tide and lunar cycle produces 9 surface elevations for each of the 37 storm events of Table 3 at the station locations shown in Figure 9. This procedure produces a total input/response vector training set of 333 (37\*9) tide plus surge events for each station location. It is also considered that the mid-tide level would have twice the probability of occurrence on the MHHW or the MLLW. Similarly the mean tidal range would have twice the probability of occurrence as spring or neap tide.



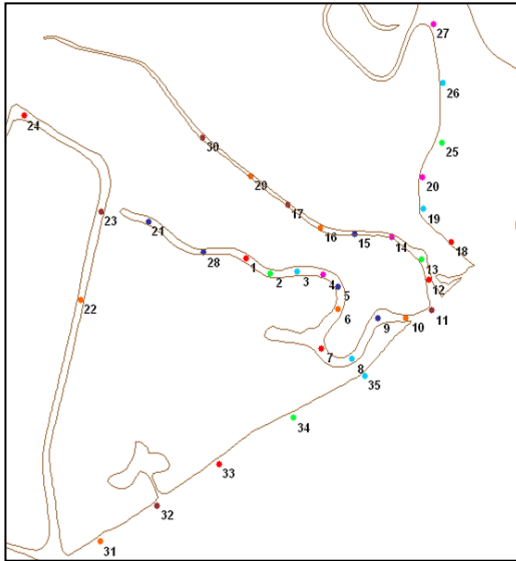


Fig. 9 Location of points used for input to EST model

The water surface elevation that is one of the response vectors for the EST analysis was calculated as follows. Analysis of tidal values for the tides at Freeport harbor show that the approximate peak tidal elevation at spring, mid, and neap cycle is 0.35, 0.268, and 0.20 m. The four primary model-generated diurnal and semi-diurnal tidal constituents for the Freeport Harbor study area are the K1, O1, M2, and S2 with the amplitudes of 0.137, 0.125, 0.07, and 0.02 m respectively. The values of spring and neap tides are calculated using these constituents as follows assuming that most of the tidal energy is contained in these constituents, using the relationship:

spring high tide	=K <sub>1</sub> + O <sub>1</sub> + M <sub>2</sub> + S <sub>2</sub>
mid spring/neap high tide	=K <sub>1</sub> + O <sub>1</sub>
neap high tide	= K <sub>1</sub> - O <sub>1</sub> + M <sub>2</sub> + S <sub>2</sub>

This relationship generates an acceptable approximation of 0.352, 0.261, and 0.191 m versus 0.35, 0.268, and 0.2 m for the 9 combinations of astronomical and lunar tidal effects. Therefore this relationship was used for all locations.

**4.4 Storm Consistency with Past Events**

The first major requirement for the use of EST is that future events will be statistically similar to past events. This criterion is maintained by insuring that the input vectors for simulated events are similar to

those of past events and the input vectors have similar joint probabilities to those historical events of the training set. For example, a typhoon with a large central pressure deficit and low maximum winds is not a realistic event – the two parameters are not independent although their precise dependency is unknown. The simulation of realistic events is accounted for in the nearest-neighbor interpolation-bootstrap-resampling technique developed by Borgman (Scheffner, et al. 1999 and Borgman, et al. 1992). By using the training set as a basis of for defining future events, unrealistic events are not included in the life cycle of events generated by the EST.

The basic technique can be described as follows. Let X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub>, . . . X<sub>n</sub> be n independent, identically distributed random vectors (historic storm events) each having two components [X<sub>i</sub>={x<sub>i</sub>(1),x<sub>i</sub>(2)}; i =1,n]. If there are no hypothetical events, each event X<sub>i</sub> has a probability p<sub>i</sub> of 1/n. If one storm event is used to generate two hypothetical events, then the original storm and each of the two perturbations are assigned a probability of one-third of 1/n. A cumulative probability relationship can be developed in which each storm event of the total training set of 333 surge plus tide events is assigned a segment of the total probability of 0.0 to 1.0. Therefore each event occupies a fixed portion of the 0.0 to 1.0 cumulative probability space according to the total number of events in the training set. A random number from 0 to 1 is then used to identify a storm event from the total storm training set population. The procedure is equivalent to drawing and replacing a random sample from the full storm event population.

The process can be summarized as follows. Select a specific storm event from the training set and proceeds to the location in multidimensional input vector space corresponding to that event. From that location, perform a nearest neighbor random walk to define a new set of input vectors. This new input vector defines a new storm, similar to the original storm but with some variability in parameters.

**4.5 Storm Event Frequency**

The second criteria to be satisfied is that the number of storm events selected per year must be statistically similar to the number of historical events that have occurred at the area of concern. Given the mean frequency of storm events for a particular region, a Poisson distribution is used to determine the average

number of expected events in a given year. For example, a Poisson distribution can be written in the following form:

$$\Pr(s; \lambda) = \frac{\lambda^s e^{-\lambda}}{s!} \quad (6)$$

for  $s=0,1,2,3,\dots$ . The probability  $\Pr(s;\lambda)$  defines the probability of having  $s$  events per year where  $\lambda$  is the historically based number of events per year.

In the present study, historical data were used to define  $\lambda$  as:

$$\lambda = 0.2307 \text{ (27 historical events/117 years or one event every 4.33 years)}$$

Output from the EST program is  $N$  repetitions of  $T$  years of simulated storm event responses. For this study,  $N = 500$  repetitions of a  $T = 200$  year sequence of storm activity are used. It is from the responses of those 500 life cycle simulations that frequency-of-occurrence relationships are computed. Because EST output is of the form of multiple time-series simulations, post processing of output yields mean value frequency relationships with definable error estimates. The computational procedure followed is based on the generation of a probability distribution function corresponding to each of the  $T$ -year of simulated data. In the following section, the approach adopted for using these storms to develop frequency-of-occurrence relationships is given.

#### 4.6 Risk-Based Frequency Analysis

The primary justification for applying the EST to a specific project is to generate risk-based frequency information relating to effectiveness and cost of the project with the level of protection provided. The multiple life-cycle simulations produced by EST can be used for developing design criteria in two approaches. In the first, the actual time series are input to an economics based model that computes couple storm inundation, structure response, and associated economics. The model internally computes variability associated with the risk-based design. The other application is the post processing of multiple time-series to generate single-response frequency relationships and associated variability.

#### 4.7 Frequency-of Occurrence Relationships

Estimates of frequency-of-occurrence begin with the calculation of a probability distribution function (pdf) for the response vector of interest. Let  $X_1, X_2, X_3, \dots, X_n$  be  $n$  independent, identically distributed, random response variables with a cumulative pdf given by

$$F_x(x) = \Pr [ X < x ] \quad (7)$$

where  $\Pr[X < x]$  represents the probability that the random variable  $X$  is less than or equal to some value  $x$ , and  $F_x(x)$  is the cumulative probability density function ranging from 0.0 to 1.0. The problem is to estimate the value of  $F_x$  without introducing some parametric relationship for probability. The following procedure is adopted because it makes use of the probability laws defined by the data and does not incorporate any prior assumptions concerning the probability relationship.

Assuming a set of  $n$  observations of data, the  $n$  values of  $x$  are first ranked in order of increasing size. In the following analysis, the parentheses surrounding the subscript indicate that the data have been rank-ordered. The value  $x(1)$  is the smallest in the series and  $x_{(n)}$  represents the largest value. Let  $r$  denote the rank of the value  $x(r)$  such that rank  $r = 1$  is the smallest and rank  $r = n$  is the largest.

An empirical estimate of  $F_x(x(r))$ , denoted by  $F_x(x_{(r)})$ , is given by Gumbel (1954) and Borgman and Scheffner (1991) as:

$$F_x(x_{(r)}) = \frac{r}{(n+1)} \quad (8)$$

for  $\{x_{(r)}, r = 1, 2, 3, \dots, n\}$ . This form of estimate allows for future values of  $x$  to be less than the smallest observation  $x_{(1)}$  with a cumulative pdf of  $1/(n+1)$ , and to be larger than the largest values with cumulative pdf of  $n/(n+1)$ .

The cumulative pdf as defined by Equation 8 is applied to develop stage-frequency relationships as follows. Consider that the cumulative probability for an  $n$ -year return period storm can be written as

$$F(n) = 1 - \frac{1}{n} \quad (9)$$

where  $F(n)$  is the simulated cumulative pdf for an event with a return period of  $n$  years. Frequency-of-occurrence relationships are obtained by linearly interpolating a stage from Equation 8 corresponding to the pdf associated with the return period calculated by Equation 8.

Equations 8 and 9 are applied to each of the  $N$ -repetitions of  $T$ -years of storm events simulated via the EST. Therefore, there are  $N$  frequency-of-occurrence relationships generated. From these results, the standard deviation is determined to provide an estimate of the variability of the result. The standard deviation is computed for each return period as:

$$\sigma = \sqrt{\left[ \frac{1}{N} \sum_{n=1}^N (x_n - \bar{x})^2 \right]} \quad (10)$$

where  $\bar{x}$  is the mean value of  $x$ . An example set of 500 frequency relationships and the mean value for the Freeport Harbor are shown in Figure 10. Figure 11 shows the mean value with the  $\pm$  one standard deviation error bounds. The extreme event storm surge for locations around the Freeport levee for 200, 100 and 50 year storms are shown in Figures 12-14.

Surge elevations are affected by many variables such as offshore bathymetry, storm/shoreline orientation, location with respect to the Gulf of Mexico, and the local topography. Therefore, the frequency-indexed surge distribution varies from one end of the project to the other.

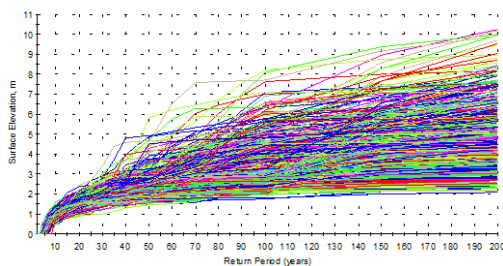


Fig. 1 Frequency relationship for the Freeport Harbor Example Case for 500 simulations of 200 years

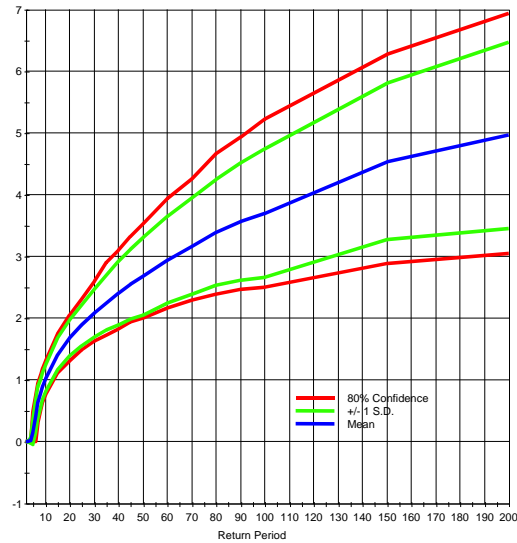


Fig. 2. Mean Value Frequency with standard deviation bounds for Freeport Harbor

The objective of this study is to provide information to analyze whether the existing levee structures in Freeport provide sufficient protection. The levee elevations all along the existing network was obtained from the US Army Corps survey and imported in a GIS based model and subsequently used in the SMS interface. The existing levee structure is as shown in Figure 12 with vertical elevations in meters referenced to NAD 83 vertical datum. This information is further used to obtain “remaining freeboard” elevations, which refers to how much of the existing levee structure will remain above water in the case of extreme events. These values will be noted all along the existing structure.

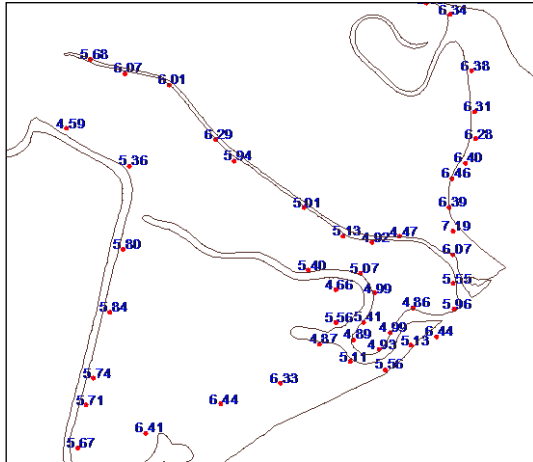


Fig. 12. Levee Elevation in meters along Freeport

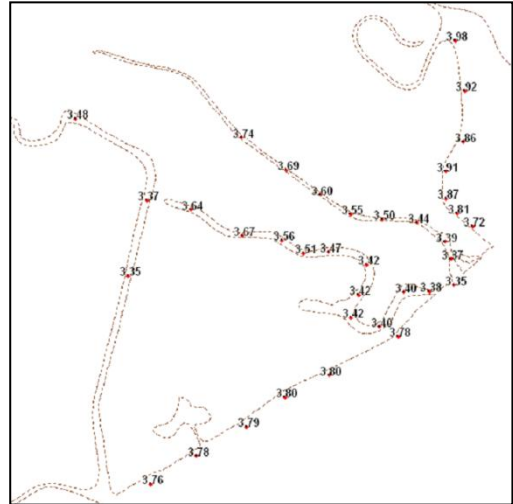


Fig. 4. 100 year storm surge values around the Freeport Levee System

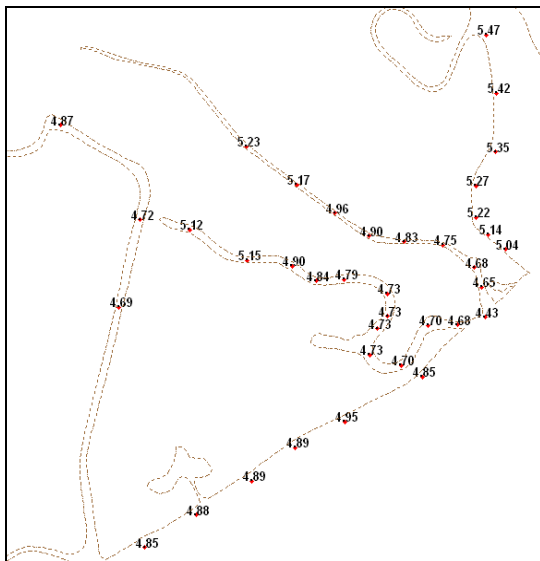


Fig. 3. 200 year storm surge values around the Freeport Levee System

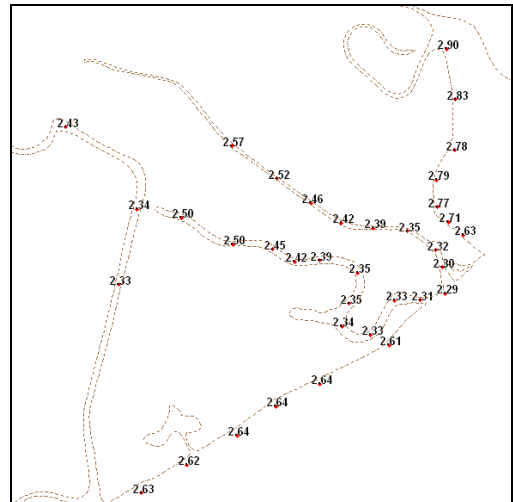


Fig. 5. 50-year storm surge values around the Freeport Levee System

### 5. Conclusions

This report describes an approach for determining the risk associated with tropical storms and typhoons affecting a local area. This is accomplished by generating storm surge plus tide frequency-of-occurrence relationships. These relationships are based on numerical simulations of tidal elevations and storm surges for tropical storm events that have historically impacted the study area. Simulations are made using the long-wave hydrodynamic model ADCIRC. The model re-

sults are analyzed with the EST statistical simulation model to produce multiple life-cycle simulations of tide and storm surge activity along the coast to generate water surface elevation versus frequency-of-occurrence relationships for selected locations within the study area. A detailed example is given for the case of Freeport, Texas. The study produced the 200-year storm event as well as the 100-year and the 50-year storm conditions. However, none of the storm surge plus tide values were greater than the current height of the levee system.

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