Evaluation of Improvements to the Freeport, Texas Ship Channel Under Hurricane-Induced Storm Surge Conditions

David J. Mark

Prepared for U.S. Army Engineer District, Galveston

Preface

The U.S. Army Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory (CHL) was requested by the Galveston District to investigate whether planned improvements to the Freeport Ship Channel will make areas in Freeport Harbor more susceptible to hurricane-induced inundation. Improvements include removing part of the peninsula (Velasco Drainage District North Wave Barrier) separating the Gulf Intracoastal Waterway (GIWW) and Freeport Harbor, and the jetty and entrance channels are proposed to be widened to the southwest.

A frequency-of-occurrence analysis was recently completed for Freeport, Texas and is reported in Edge et al. (2004). As part of that analysis, a high-resolution ADCIRC model was developed for the Harbor areas in the vicinity, and historical storm events were simulated with the model for estimating the peak water-surface elevations induced by these tropical storms. Tasks performed for this study included: 1) upgrading the ADCIRC model developed by Edge et al. (2004) such that it represents the planned Harbor configuration; 2) simulate two hurricanes for both the existing and planned Harbor conditions that induced moderate to significant storm surge; and 3) compare model-generated water-surface elevations produced with the existing- and planned-configuration models at several locations within the Harbor and in its vicinity.

This study was conducted for the SWG by the ERDC Coastal and Hydraulics Laboratory (CHL). Ms. Lynn Vera (SWG) served as the senior coastal engineer.

This study was conducted by Mr. David J. Mark, Estuarine Engineering Branch (HF-E), Flood and Storm Protection Division (HF), CHL. Direct supervision was provided by Dr. Robert T. McAdory, Chief, Estuarine Engineering Branch, and Mr. Bruce A. Ebersole, Chief, Flood and Storm Protection Division. COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

The U.S. Army Corps of Engineers District, Galveston (SWG) requested the U.S. Army Engineer Research and Development Center's Coastal and Hydraulics Laboratory to perform a cursory-level numerical study to determine whether planned improvements to the Freeport, Texas Ship Channel will make Freeport Harbor and adjacent, low-lying areas more susceptible to inundation due to hurricane-induced storm surge. Planned improvements include:

a. Deepening the Federally-maintained channel from 45 ft. to 64 ft mean-low-tide (mlt) to accommodate larger ocean-going vessels.
b. Increasing the size of the Brazosport Turning basin by removing a portion of the southeastern peninsula (North Wave Barrier) that separates the GIWW from the Harbor proper.
c. Extending the South Wave Barrier (located in Quintana) in the southwesterly direction approximately 2,000 feet.
d. Straightening the northeasterly-most 1700 feet of the South Wave Barrier.

The Planetary Boundary Layer (PBL) and ADvanced CIRCulation (ADCIRC) numerical models were selected for estimating hurricane-induced storm surge elevations. Atmospheric pressure and wind fields are generated with the PBL mode and subsequently used as input to the ADCIRC model, which predicts the storm surge levels. Both models were applied in the coastal erosion study sponsored by the SWG and reported in Scheffner, et al (2002), as well as the storm surge study conducted by Edge et al. (2004) for the Velasco, Texas Drainage District.

As part of this analysis, the existing high-resolution ADCIRC model was adapted to depict the planned Harbor configuration. Hurricanes selected for simulating are based on the September 1941 hurricane (storm number 405) and Hurricane Fern (storm number 704), which impacted the Texas coast in September 1971. After completing the storm surge simulations, model-generated water-surface elevations produced with the existing- and planned-configuration models were compared at several locations within the Harbor and in its vicinity for determining whether the improvements will make the Harbor more susceptible to hurricane-induced storm surges.

2 Application of Hurricane and Storm Surge Models

Typically, a storm surge study requires completion of the following three sequential modeling tasks: 1) grid development; 2) calibration of the storm surge model; and, 3) verification of model results for tides and storms. For this study, however, an existing calibrated, high-resolution model of Freeport, Texas was used instead. Two modifications were made to the existing model, however. First, the nodal resolution of the Ship Channel and Harbor was increased in order to improve the resolution of the plan configuration; the original model lacked sufficient resolution to accurately depict the differences between the base and plan configuration. Second, low-lying areas adjacent to the Harbor were included in the numerical grid. The study area is presented in Figure 1. Figures 2 through 4 present the numerical grid. Minimum node-to-node spacing in the study area is approximately 100 ft (30 m).

The hurricane wind field model used in conjunction with the ADCIRC model is the Planetary Boundary Layer (PBL) model (Cardone, Greenwood, and Greenwood 1992). This model simulates hurricane-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. The radius to maximum wind is approximated using a nomograph that incorporates the maximum wind speed and atmospheric pressure anomaly (Jelesnianski and Taylor, 1973). 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.

Hurricanes selected for simulation in this study are based on the September 1941 hurricane (storm number 405) and Hurricane Fern (storm number 704), which impacted

the Texas coast in September 1971. The hurricane parameters described above for the September 1941 hurricane and Hurricane Fern were obtained from the National Oceanic and Atmospheric Administration's (NOAA) HURricane DATabase (HURDAT) of tropical storm events (Jarvinen, Neumann, and Davis 1988). The database contains latitude and longitude locations of the eye of the hurricane with the corresponding central pressure and maximum wind speeds at 6-hour intervals.

These hurricanes were selected for simulation because both came within close proximity of the study area and produced relatively high surges. (Stronger hurricanes, such as the 1900 Hurricane, were omitted from this analysis because they would have generated significantly greater overland flooding; this, in turn, hampers determining whether the planned improvements make the Harbor more susceptible to storm surge.) Furthermore, the two hurricanes provided two angles-of-approach; the 1941 hurricane approached the coast from southwest, whereas Hurricane Fern skirted the coast while moving from the northeast to the southwest. The eye wall of both hurricanes passed directly over the Harbor. To provide a more typical or representative storm event, the tracks of each were shifted by 0.5 degrees. The track of the 1941 Hurricane was shifted 0.5 degrees to the west, whereas, Hurricane Fern was shifted 0.5 degrees to the south. Figures 5 and 6 depict the track of each hurricane.

The two hurricanes were simulated with the ADCIRC model, without tide, for the base and plan Harbor configuration. Time-series of water-surface elevation were compared at 3 sites within the Harbor. Figure 8 displays these sites. Figures 9 through 11 compare time-series of storm surge levels for Hurricane Fern, whereas Figures 12 through 14 compare time-series of storm surge levels for the 1941 hurricane.

This modeling exercise found little change in peak water-surface elevations within the Harbor resulting from the planned improvements. Estimated increases were about 0.05 m (0.16 ft) for the hurricane that is based on the September 1941 storm. Similar increase in storm surge was found for the storm based on Hurricane Fern. Consequently, the planned Harbor improvements do not appear to make the Harbor and adjacent low-lying areas more susceptible to storm surge from less intense hurricanes.

Figure 1. Aerial photograph of Freeport Harbor, Texas.

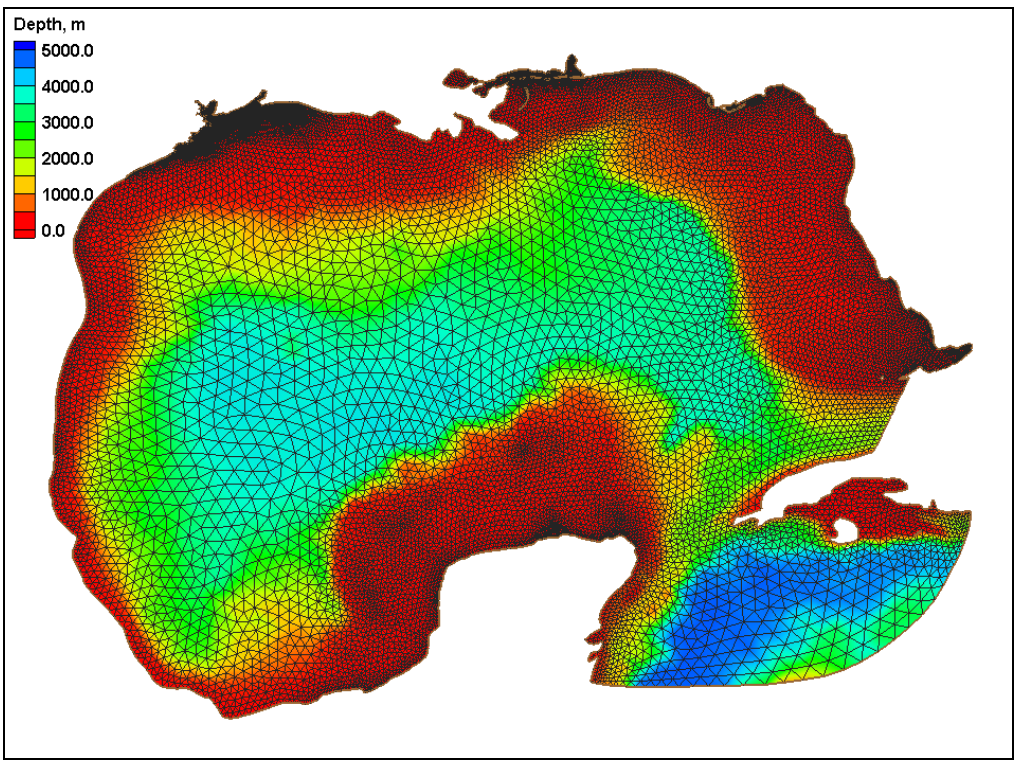

Figure 2. Numerical Grid.

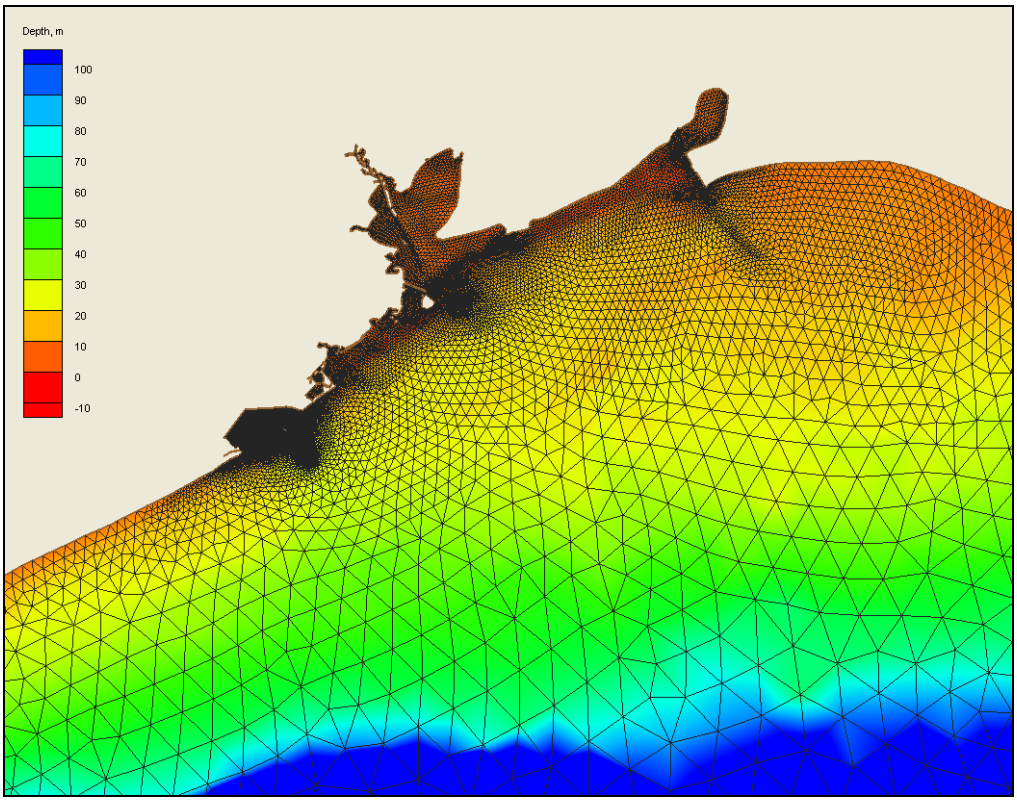

Figure 3. Numerical grid in vicinity of northern Texas coast.

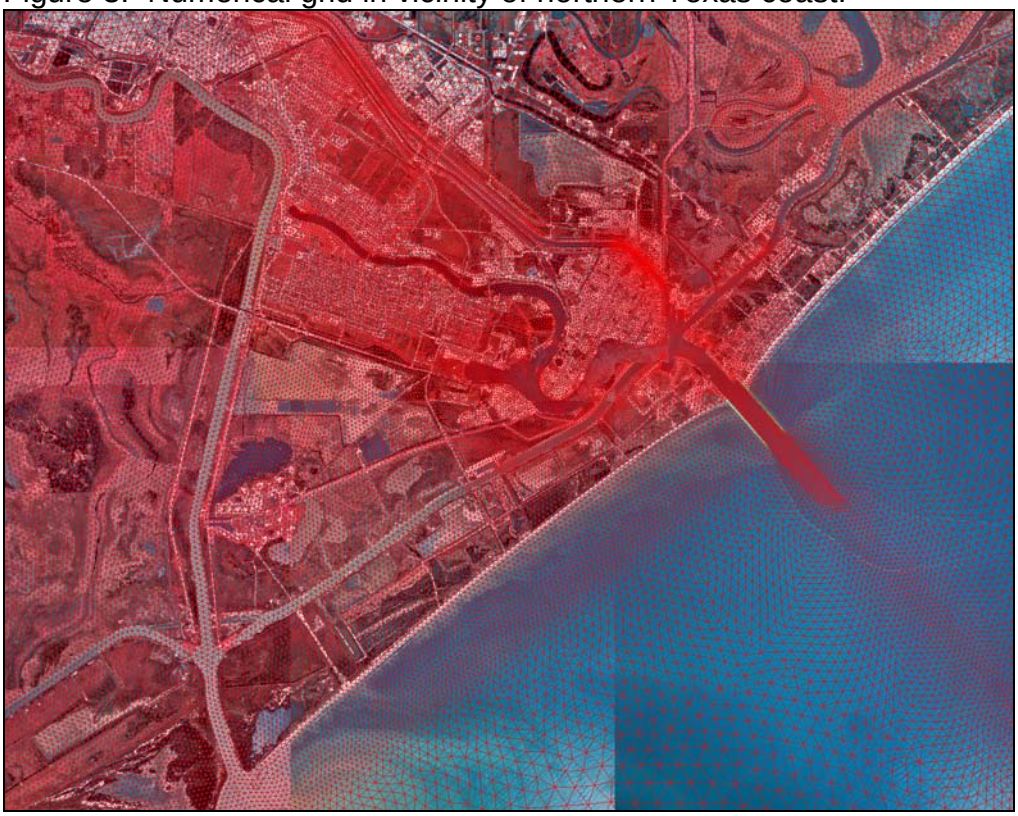
Figure 4. Numerical grid in vicinity of Freeport, Texas.

Figure 5. Numerical grid in vicinity of Freeport Harbor, Texas (overland portion of grid has been omitted for illustration purposes).

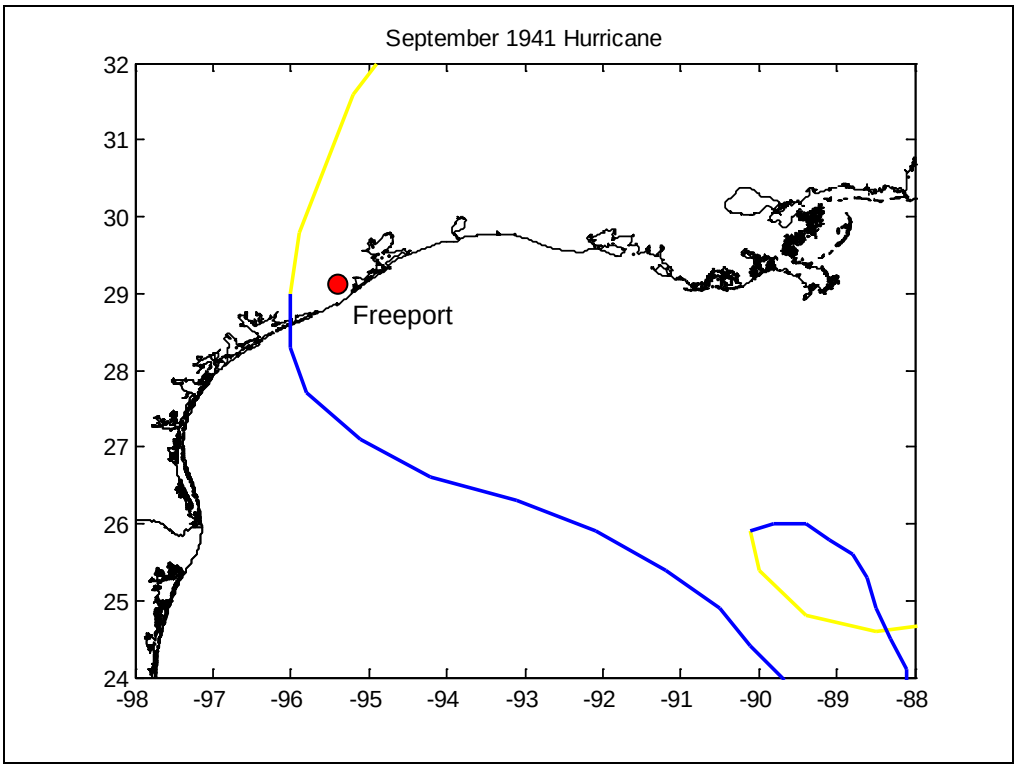

Figure 6. Modeled track for the September 1941 hurricane (Hurricane 405).

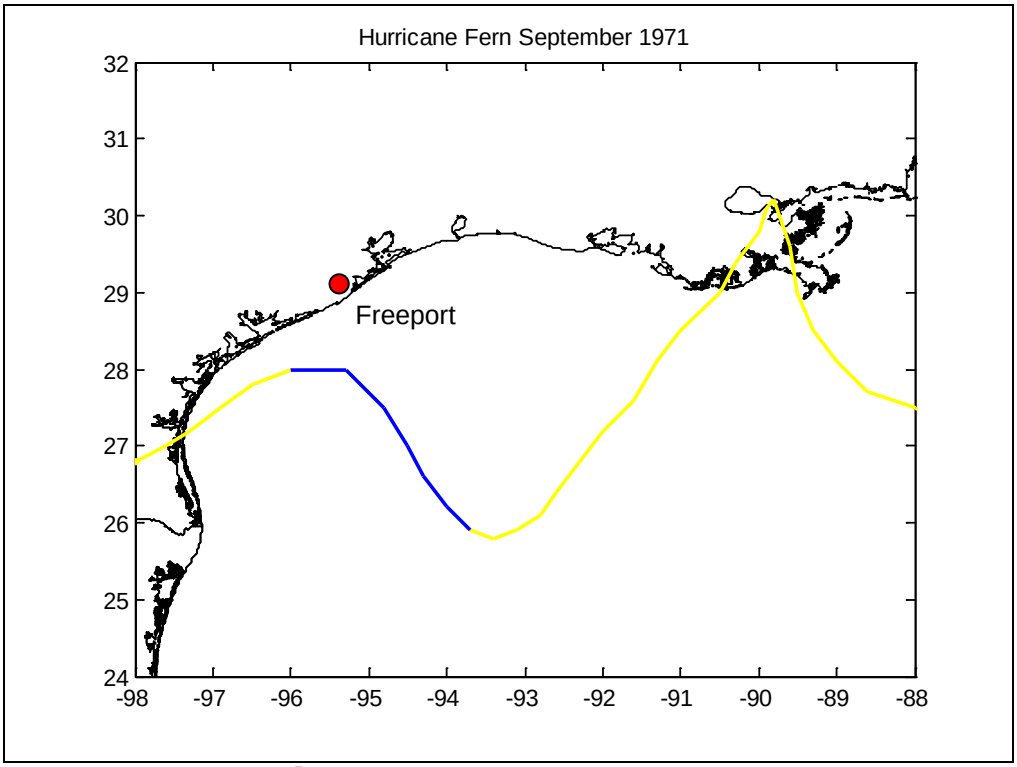

Figure 7. Modeled track for Hurricane Fern.

Figure 8. Comparison locations.

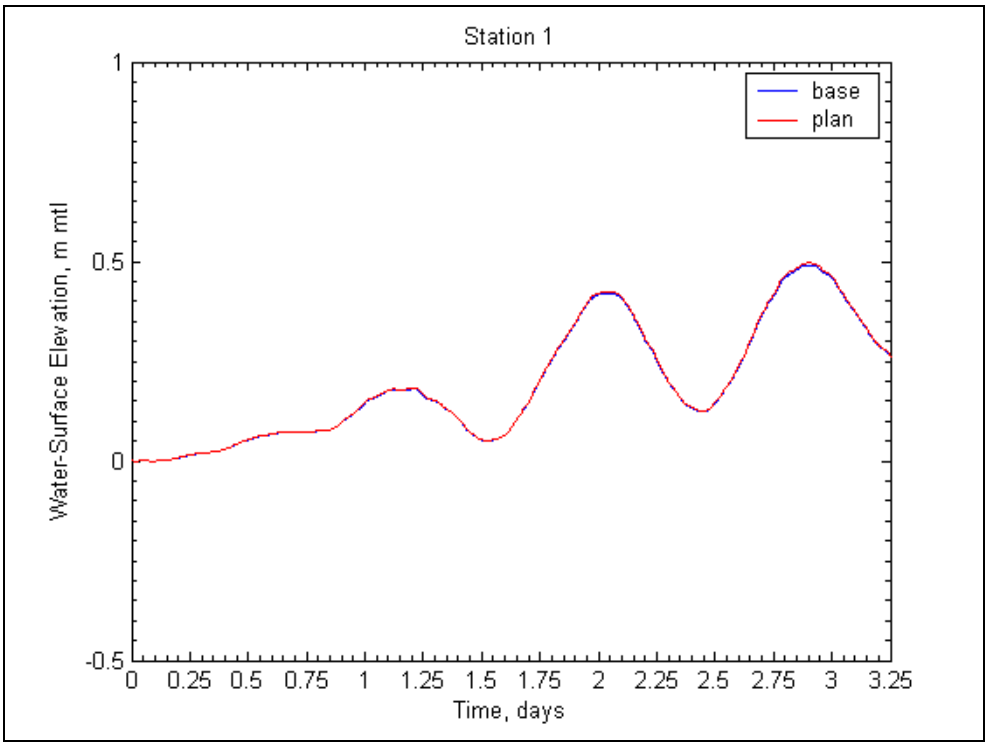

Figure 9. Comparison of storm surge time-series for base and planned harbor configurations at station 1 for hurricane 704.

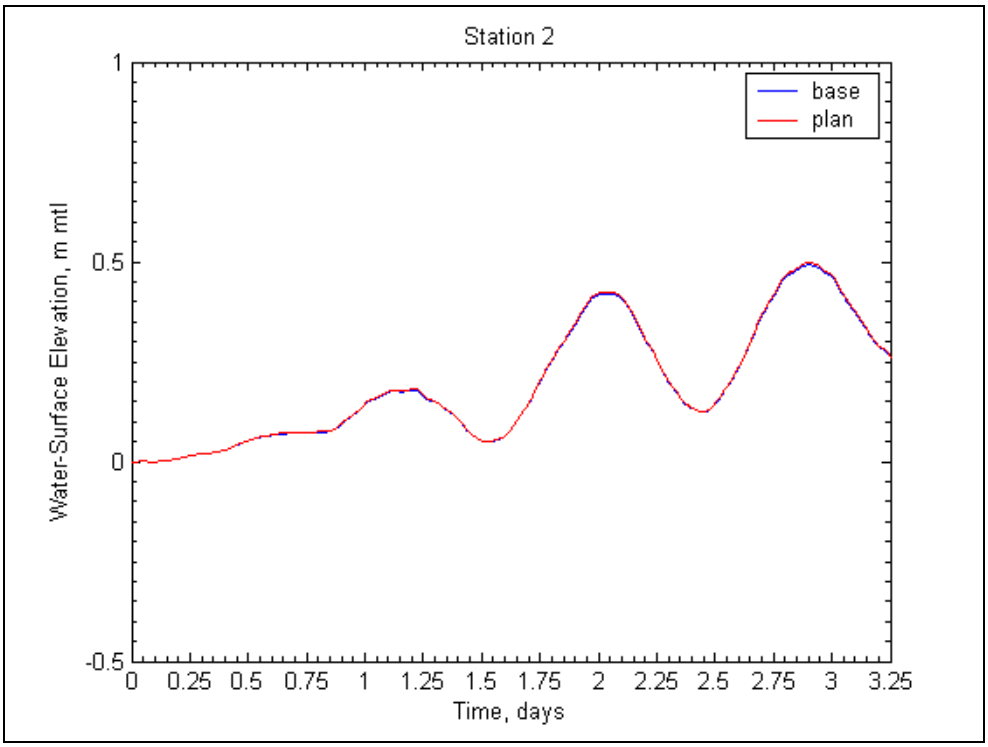

Figure 10. Comparison of storm surge time-series for base and planned harbor configurations at station 2 for hurricane 704.

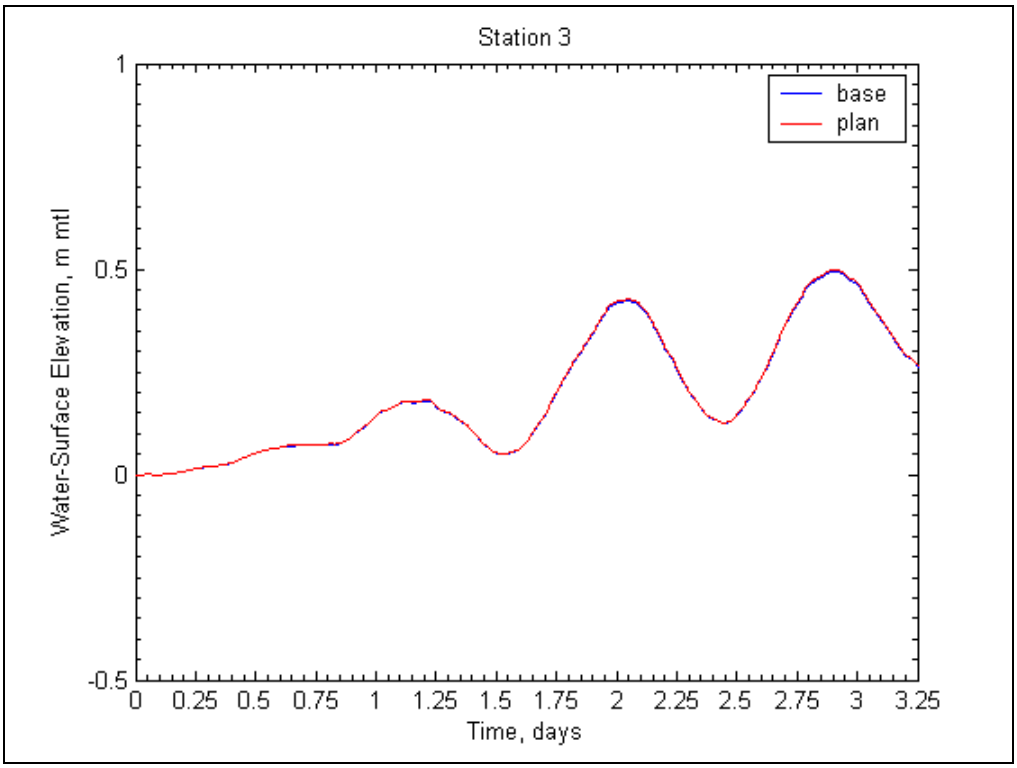

Figure 11. Comparison of storm surge time-series for base and planned harbor configurations at station 3 for hurricane 704.

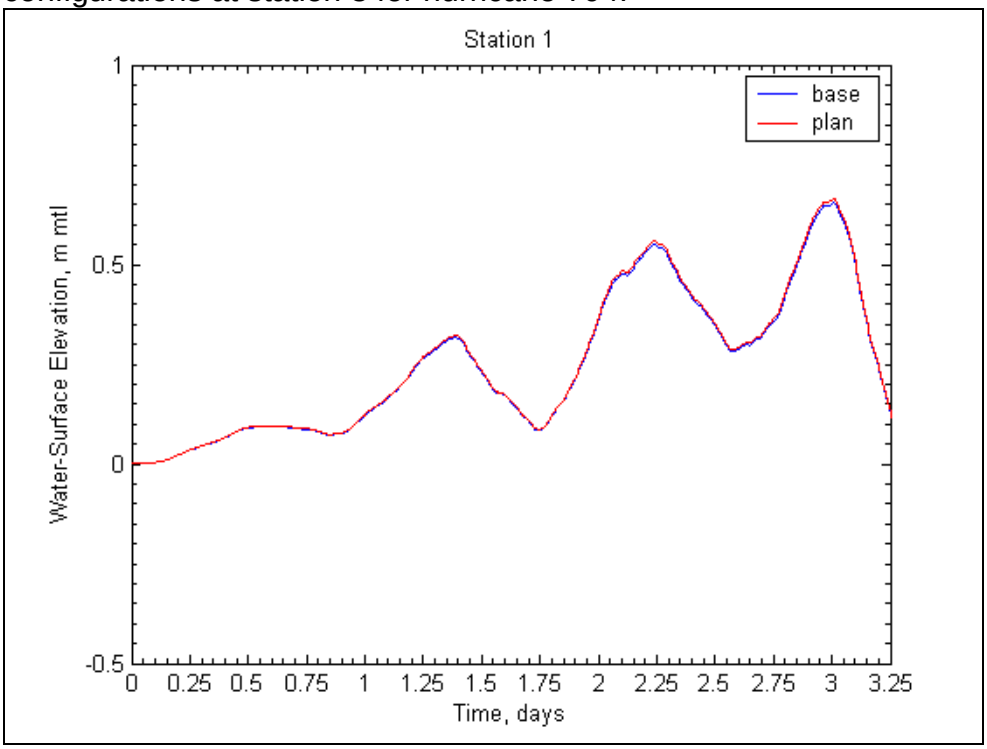

Figure 12. Comparison of storm surge time-series for base and planned harbor configurations at station 1 for hurricane 405.

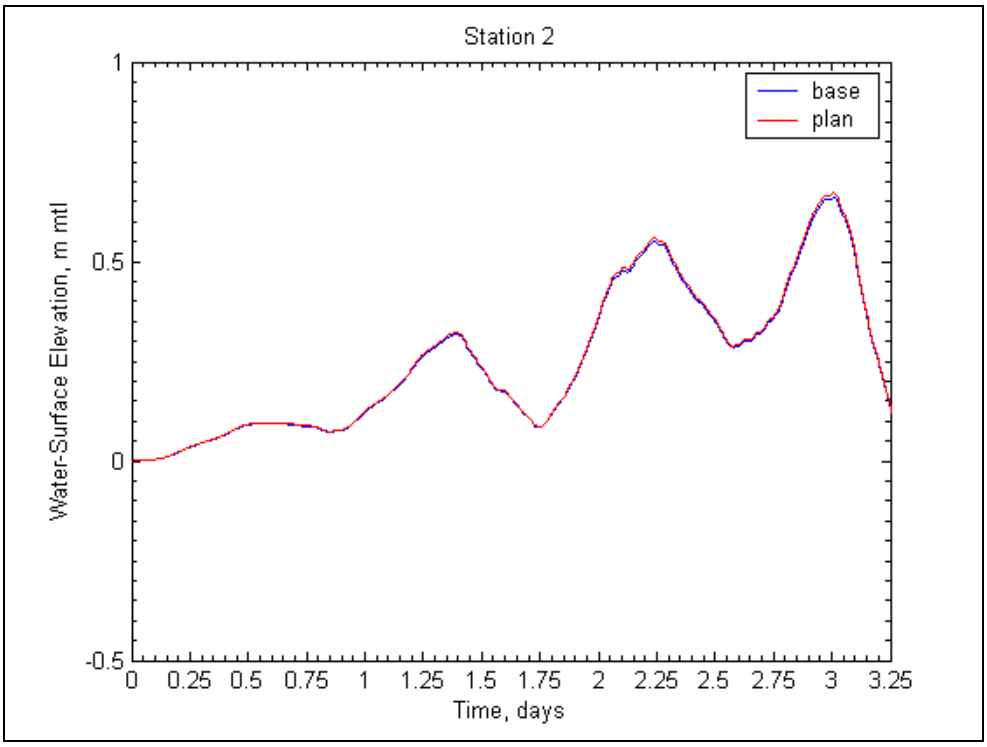

Figure 13. Comparison of storm surge time-series for base and planned harbor configurations at station 2 for hurricane 405.

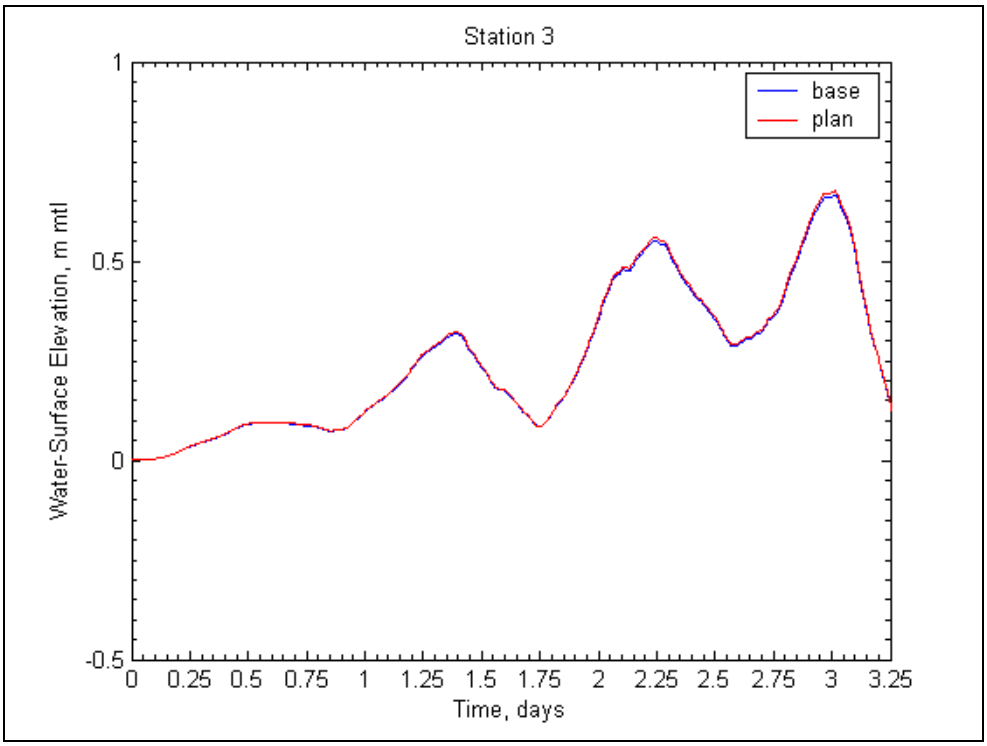

Figure 14. Comparison of storm surge time-series for base and planned harbor configurations at station 3 for hurricane 405.

3 Conclusions

The U.S. Army Engineer Research and Development Center's Coastal and Hydraulics Laboratory performed a cursory-level numerical storm surge study to determine whether planned improvements to the Freeport, Texas Ship Channel and Harbor will make the Freeport Harbor and adjacent, low-lying areas more susceptible to hurricane-induced inundation. Planned improvements include:

a. Deepening the Federally-maintained channel from 45 ft. to 64 ft mean-low-tide (mlt) to accommodate larger ocean-going vessels.
b. Increasing the size of the Brazosport Turning basin by removing a portion of the southeastern peninsula (North Wave Barrier) that separates the GIWW from the Harbor proper.
c. Extending the South Wave Barrier (located in Quintana) in the southwesterly direction approximately 2,000 feet.
d. Straightening the northeasterly-most 1700 feet of the South Wave Barrier.

A calibrated high-resolution model of Freeport Harbor was applied, for base and planned configurations, to make this assessment. Two hurricanes were simulated in this study, and were based on the September 1941 hurricane and Hurricane Fern, which occurred in September 1971. Wind and atmospheric pressure fields were developed using the PBL model, and its output were subsequently used as input in the ADCIRC storm surge model.

This modeling exercise found little change in peak water-surface elevations within the Harbor resulting from the planned improvements. Estimated increases were about 0.05 m (0.16 ft) for the hurricane that is based on the September 1941 storm. Similar increase in storm surge was found for the storm based on Hurricane Fern. Consequently, the planned Harbor improvements do not appear to make the Harbor and adjacent low-lying areas more susceptible to storm surge from less intense hurricanes.

References

Borgman, L.E., Miller, M.C., Butler, H.L., and Reinhard, R.D., 1992, Empirical simulation of future hurricane storm histories as a tool in engineering and Economic Analysis. ASCE Proc. Civil Engineering in the Oceans V. College Station, TX. 2-5 November 1992.

Borgman, L.E. and Scheffner, N.W., 1991, The simulation of time sequences of wave height, period, and direction. TR-DRP-91-2. USAE WES. Vicksburg, MS.

Cardone, V.J., Greenwood, C.V., and Greenwood, J.A., 1992, “Unified Program for the Specification of Hurricane Boundary Layer Winds Over Surfaces of Specified Roughness,” contract Report CERC-92-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Flather, R. A. 1988, “A numerical model investigation of tides and diurnal-period continental shelf waves along Vancouver Island,” Journal of Physical Oceanography 18,115-139.

Garcia, Andrew W. and Flor, Thomas H., 1984, "Hurricane Alicia Storm Surge and Wave Data," Technical Report CERC-84-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Griffis, F.H., Jettmar, Charles E., Pagdadis, Sotiris, and Tillman, Russel K., 1995, “Dredging Research Program Benefit Analysis,” Technical Report DRP-95-8, September 1995, U.S. Army Engineer Waterways Experiment Station, Vicksburg MS.

Gumbel, E.J., 1954, Statistical theory of extreme value and some practical application. National Bureau of Standards Applied Math. Series 33. U.S. Gov. Publ. Washington, DC.

Harris, D.L., 1963, “Characteristics of the Hurricane Storm Surge,” Technical Paper No. 48, U.S. Dept. of Commerce, U.S. Weather Bureau, Washington, DC.

Jarvinen, B.R., Neumann, C.J., and Davis, M.A.S., 1988, "A Tropical Cyclone Data Tape for the North Atlantic Basin, 1886-1983: Contents, Limitations, and Uses," NOAA Technical Memorandum NWS NHC 22.

Jelesnianski, C.P. and Taylor, A..D., 1973, "A Preliminary View of Storm Surges Before and After Storm Modifications." NOAA Technical Memorandum ERL WMPO-3, Weather Modification Program Office, Bounder CO.

Kolar, R. L., Gray, W. G., Westerink, J. J., and Luettich, R. A. 1994, "Shallow water modeling in spherical coordinates: Equation formulation, numerical implementation, and application," Journal of Hydraulic Research 32(1), 3-24.

Luettich, R.A., Westerink, J.J., and Scheffner, N.W., 1992, "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL", Technical Report DRP-92-6, November 1992, U.S. Army Engineer Waterways Experiment Station, Vicksburg MS.

Scheffner, N.W., Mark, D.J., Blain, C.A., Westerink, J.J., and Luettich, R.A., 1994, "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts and Estuaries Report 5: A Tropical Storm Data Base for the East and Gulf of Mexico Coasts of the United States," Technical Report DRP-92-6, August 1994, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Scheffner, N.W. and Borgman, L.E., 1992, A stochastic time series representation of wave data. ASCE Journal of Waterways, Ports, Coastal and Ocean Engineering. Vol 118, No. 4. Jul/Aug 1992.

Scheffner, Norman W., Clausner, James E., Militello, Adele, Borgman, Leon E., Edge, Billy L., and Grace, Peter E., 1999, "Use and Application of the Empirical Simulation Technique: Users Guide," Technical Report CHL-99-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, December 1999.

USACE, 1979, "Texas Coast Hurricane Study, Sabine Lake Study Segment," US Army Engineer District, Gavleston, Corps of Engineers, Galveston Texas, March 1979.

Westerink, J.J., Luettich, R.A., and Scheffner, N.W., (1993), "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts and Estuaries Report 3: Development of a Tidal Constituent Database for the Western North Atlantic and Gulf of Mexico," Technical Report DRP-92-6, June 1993, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Appendix A Description of Storm Surge Model

The ADCIRC numerical model was chosen for simulating the long-wave hydrodynamic processes in the study area. When imposing the wind and atmospheric pressure fields, the ADCIRC model can accurately replicate tide induced and storm-surge water levels and currents. The ADCIRC model was developed in the USACE Dredging Research Program (DRP) as a family of two- and three-dimensional finite element-based models (Luettich, Westerink, and Scheffner 1992; Westerink et al. 1992). An important of the model is that it can simulate tidal circulation and storm-surge propagation over very large computational domains while simultaneously providing high resolution in areas of complex shoreline configuration and bathymetry.

In two dimensions, the model is formulated using the depth-averaged shallow water equations for conservation of mass and momentum. Furthermore, the formulation assumes that the water is incompressible, hydrostatic pressure conditions exist, and that the Boussinesq approximation is valid. Using the standard quadratic parameterization for bottom stress and neglecting baroclinic terms and lateral diffusion/dispersion effects, the following set of conservation equations in primitive, non-conservative form, and expressed in a spherical coordinate system, are incorporated in the model (Flather 1988; Kolar et al. 1993):

$$\frac{\partial U}{\partial t} + \frac{1}{r\cos\phi} U \frac{\partial U}{\partial \lambda} + \frac{1}{R} V \frac{\partial U}{\partial \phi} - \left[\frac{\tan\phi}{R} U + f \right] V = - \frac{1}{R\cos\phi} \frac{\partial}{\partial \lambda} \left[\frac{p_s}{\rho_0} + g(\zeta - \eta) \right] + \frac{\tau_{s\lambda}}{\rho_0 H} - \tau_* U \tag{1}$$

$$\frac{\partial V}{\partial t} + \frac{1}{r\cos\phi} U \frac{\partial V}{\partial \lambda} + \frac{1}{R} V \frac{\partial V}{\partial \phi} - \left[\frac{\tan\phi}{R} U + f \right] U = - \frac{1}{R} \frac{\partial}{\partial \phi} \left[\frac{p_s}{\rho_0} + g(\zeta - \eta) \right] + \frac{\tau_{s\lambda}}{\rho_0 H} - \tau_* V \tag{2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\phi}\left[\frac{\partial UH}{\partial \lambda} + \frac{\partial (UV\cos\phi}{\partial \phi}\right] \qquad (3)$$

where

t = time,

λ and φ = degrees longitude (east of Greenwich is taken positive) and degrees latitude (north of the equator is taken positive),

ζ = free surface elevation relative to the geoid,

U and V = depth-averaged horizontal velocities in the longitudinal and latitudinal directions, respectively,

R = the radius of the earth,

$H = \zeta + h$ = total water column depth,

h = bathymetric depth relative to the geoid,

$f = 2\Omega \sin \varphi$ = Coriolis parameter,

Ω = angular speed of the earth,

p_s = atmospheric pressure at free surface,

g = acceleration due to gravity,

η = effective Newtonian equilibrium tide-generating potential parameter,

ρ_0 = reference density of water,

$\tau_{s\lambda}$ and $\tau_{s\varphi}$ = applied free surface stresses in the longitudinal and latitudinal directions, respectively, and

τ = bottom shear stress and is given by the expression $C_f(U^2 + V^2)^{1/2}/H$ where C_f is the bottom friction coefficient.

The momentum equations (Equations 1 and 2) are differentiated with respect to λ and τ and substituted into the time differentiated continuity equation (Equation 3) to develop the following Generalized Wave Continuity Equation (GWCE):

$$\frac{\partial^2\zeta}{\partial t^2} + \tau_0\frac{\partial\zeta}{\partial t} - \frac{1}{R\cos\phi}\frac{\partial}{\partial\lambda}\left[\frac{1}{R\cos\phi}\left(\frac{\partial HUU}{\partial\lambda} + \frac{\partial(HUV\cos\phi}{\partial\phi}\right) - UVH\frac{\tan\phi}{R}\right]$$

$$\left[-2\omega\sin\phi\, HV + \frac{H}{R\cos\phi}\frac{\partial}{\partial\lambda}\left(g(\zeta - \alpha\eta) + \frac{p_5}{[}p_0\right) + \tau_* HU - \tau_0 HU - \tau_{s\lambda}\right]$$

$$-\frac{1}{R}\frac{\partial}{\partial\phi}\left[\frac{1}{R\cos\phi}\left(\frac{\partial HVV}{\partial\lambda} + \frac{\partial HVV\cos\phi}{\partial\phi}\right) + UUH\frac{\tan\phi}{R} + 2\,\omega\sin\phi\, HU\right] \qquad (4)$$

$$+\frac{H}{R}\frac{\partial}{\partial\phi}\left(g(\zeta - alfa\eta) + \frac{p_s}{\rho_0}\right) + \tau_* - \tau_0 HV - \frac{\tau_{s\lambda}}{\rho_0}]$$

$$-\frac{\partial}{\partial t}[\frac{VH}{R}\tan\phi] - \tau_0[\frac{VH}{R}\tan\phi] = 0$$

The ADCIRC-2DDI model solves the GWCE in conjunction with the primitive momentum equations given in Equations 1 and 2. The GWCE-based solution scheme eliminates several problems associated with finite-element programs that solve the primitive forms of the continuity and momentum equations, including spurious modes of oscillation and artificial damping of the tidal signal. Forcing functions include time-varying water-surface elevations, wind shear stresses, atmospheric pressure gradients, and the Coriolis effect.

The ADCIRC model uses a finite-element algorithm in solving the defined governing equations over complicated bathymetry encompassed by irregular sea/ shore boundaries. This algorithm allows for extremely flexible spatial discretizations over the entire computational domain and has demonstrated excellent stability characteristics. The advantage of this flexibility in developing a computational grid is that larger elements can be used in open-ocean regions where less resolution is needed, whereas smaller elements can be applied in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details.