COASTAL PROTECTION SYSTEMS AND HURRICANE IKE STORM SURGE MODELING USING ADCIRC

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ABSTRACT

There is increasing interest in coastal protection to minimize the losses and inundation of sea water and oil spills on to land. Both natural (wetlands) and man-made protection systems can be used to minimize the losses due to storm surge and oil spills. Also there is greater interest in modeling the various events to develop the needed resilient protection systems. In this study, storm surge due to Hurricane IKE in Galveston was predicted using the Advanced Circulation (ADCIRC) model. In this study a scale of 1:250,000 was used for the modeling about 170 miles of coastline and the predicted height of the storm surge was over 14 feet as compared to 15 to 20 feet reported by NOAA. Also the scale effects and sensitivity of ADCIRC was investigated so as to use it for modeling the coastal protection systems.

INTRODUCTION

The Galveston Hurricane of 1900, a Category 4 hurricane that struck Galveston, Texas, drove a devastating surge ashore; between 6,000 and 12,000 lives were lost, making it the deadliest natural disaster ever to strike the United States. The deadliest storm surge caused by an extratropical cyclone in the twentieth century was the North Sea flood of 1953, which killed a total of over 2,000 people in the UK and the Netherlands. In 2004, tsunami in the Indian Ocean with storm surges in many countries killed over 300,000 people. In 2010, earthquake coupled with tsunami resulted in a storm surge and damage to a nuclear power plant in Japan causing many losses.

The Gulf of Mexico has experienced more than average number of hurricanes in the past decade. In 2005, hurricane Katrina devastated the New Orleans, Louisiana area. In the same year hurricane Rita affected both Louisiana and Texas. Hurricane Ike in 2008 had a landfall east of Galveston Island also showed tremendous losses and has raised the need for coastal protection for the populated regions in the Gulf of Mexico. Hurricane Ike, in Texas Gulf Coast, caused approximately $30 billion in damage and killed nearly 200 people. Galveston, Houston ship channel with the port of Houston are vital for the State of Texas and for the United State government.

At present, there are only a handful of European countries that manage or construct large sea-resistant storm flood surge barriers. These are the United Kingdom, The Netherlands, Italy and Russia. After Katrina and recent oil spill experience, State of Louisiana has established a Coastal Protection and Restoration Authority (CPRA) to develop and maintain the coastal regions. Hurricane IKE in 2008 had it’s greatest impact on Texas and hence there is a need to develop coastal protection systems to minimize losses.

STORM SURGE

A storm surge is an offshore rise of water associated with a low pressure weather system, hurricanes, tsunamis and cyclones. Storm surges are mainly caused by high speed winds pushing on the ocean's surface. The wind speeds transfer the momentum to the water to pile up higher (height of storm surge) than the ordinary sea tide level. Low pressure at the center of a weather system also has a smaller secondary effect, as the bathymetry of the body of water. It is this combined effect of low pressure and persistent wind speed over a shallow water body is the main cause for the storm surge followed by overland flooding problems. When referencing storm surge height, it is important to clarify the usage, as well as the reference point. National Hurricane Center tropical cyclone reports reference storm surge as water height above predicted astronomical tide level, and storm tide as water height above NAVD (North American Vertical Datum)-88. The size of the storm surge will be influence by the size of the radius of maximum winds (RMW), radius of the wind fields, angle of the track relative to the coastline, the physical characteristics of the coastline and the bathymetry of the water offshore. Most losses during a hurricane or cyclone occur during the storm surge.

COMPUTER MODELS

Through the years, computer models were developed to estimates the storm surges generates by hurricanes. This is done using the hurricanes parameters (pressure, radius of max winds, location, direction, forward speeds) and the landing point topography and bathymetry.

The Sea, Lake, and Overland Surge from Hurricanes (SLOSH) is a computerized model developed by the National Weather Service (NWS) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes. SLOSH is used by the National Hurricane Center (NHC) for the exclusive benefit of NWS, US Army Corps of Engineers (USACE), and Emergency Management personnel (FEMA et al, 2003). It is the primary computerized model used by US official to assess a foregoing hurricanes effect on the predicted landing point to issue emergency evacuation if required.

A more research oriented application name Advanced Circulation (ADCIRC) for storm surge numerical modeling was developed (Luettich and Westerink, 2004) for better estimation of hurricane storm surge. The advantage of utilizing ADCIRC is its ability to map intricate shoreline and the corresponding topography needed to resolve complex fluid dynamics (Desback et al, 2010). ADCIRC unstructured grid allows modeling complex coastal regions at fine spatial scale (Chu et al, 2010).

OBJECTIVE

The overall objective is to review the state of the knowledge on various coastal protection systems and demonstrate the potential of using ADCIRC to model the storm surge in the Texas Gulf Coast.

1. COASTAL PROTECTION SYSTEMS

Storm surge can result in a wide variety of environmental impacts on different spatial and temporal scales. It can destroy coastal habitats such as coastal wetlands and estuaries and can erode dune systems. These places are characterized by their high biological diversity therefore storm surge can cause significant biodiversity loss and potentially species extinctions. In addition to this, these coastal features are the coasts natural buffering system against storm waves; consistent coastal flooding and sea level rise can cause this natural protection to be reduced allowing waves to penetrate greater distances inland exacerbating erosion and furthering coastal flooding. Inundation of seawater during storm surge can also cause salination of agriculturally productive soils thus resulting in a loss of productivity for long periods of time. Food crops and forests can be completely killed off by salination of soils or wiped out by the movement of flood waters. Coastal freshwater bodies including lakes, lagoons and coastal freshwater aquifers can also be affected by saltwater intrusion. This can destroy these water bodies as habitats for freshwater organisms and sources of drinking water for towns and cities.

NATURAL BARRIERS

The coast does provide natural protective structures to guard against coastal flooding. These include physical features like gravel bars and sand dune systems but also ecosystems such as salt marshes and mangrove forests have a buffering function. Mangroves and wetlands are often considered to provide significant protection against storm waves, tsunamis and shoreline erosion through their ability to attenuate wave energy. Therefore to protect the coastal zone from storm surge, these natural defenses should be protected and maintained.

It has long been argued that coastal wetlands provide critical protection against incoming hurricane storm surges, and that restoration of lost wetlands should be a key component of any strategy to protect vulnerable regions such as New Orleans. But exactly how much protection do wetlands afford? This has been a contentious issue, and there is no one number that works to define the value of wetlands in protecting against storm surge. In fact, in some cases, wetlands do not reduce the storm surge at all.

Historically, many people have used the rule of thumb that each 2.7 miles of marsh knocks down the storm surge by 1 foot (1 meter reduction per 14.5 km of marsh). This estimate is based on a US Army Corps of Engineers report from 1963 (USACE, 1963), which examined the inland penetration of the storm surge from seven storms in southern Louisiana between 1909 and 1957. However, the data from this study varied by about a factor of three--attenuation rates as high as 1 foot per 1.3 miles of marsh were seen in one storm, and as low as 1 foot per 3.8 miles of marsh in another.

Wetlands will always act to slow down the inland penetration of a storm surge, so the surge will not be able to advance very far inland before the winds die down if a region is exposed to strong winds for a short period of time. One example of this was in western Louisiana during Hurricane Rita of 2005. As the hurricane approached western Louisiana at 11 - 14 mph, the coast was initially subjected to offshore winds that blew water away from land. In the final few hours before landfall, the counter-clockwise circulation of air around the hurricane brought on-shore winds and a storm surge of up to 15 feet to the western Louisiana coast. However, this portion of the coast was only subject to on-shore winds for a few hours, and the surge was reduced by the wetlands by 1 foot per 2.1 - 3.6 miles of inland penetration, according to an ADCIRC storm surge model by Resio and Westerink (2008).

ENGINEERED BARRIERS

There are a variety of ways in which humans are trying to prevent the flooding of coastal environments. Typically this is through so called hard engineering structures such as seawalls and levees. This armouring of the coast is typically to protect towns and cities which have developed right up to the beachfront. Enhancing depositional processes along the coast can also help prevent coastal flooding. Structures such as groynes, breakwaters and artificial headlands promote the deposition of sediment on the beach thus helping to buffer against storm surges as the wave energy is spent on moving the sediments in the beach than on moving water inland. Also in recent years a new shutter system which can be adopted with seawall and dikes have been proposed (Vipulanandan 2010).

2. HURRICANE IKE

In the past 100 years, Galveston has had the highest number of hurricanes. In this study, Hurricane IKE was modeled to simulate the storm surge that occurred in Bolivar Peninsula (east of Galveston Island) using Advanced Circulation (ADCIRC). Hurricane IKE was a category 2 and had landfall on September 13, 2008. The path of Hurricane IKE is shown in Fig. 1. The advantage of ADCIRC usage for numerical modeling was investigated to resolve complex fluid dynamics in shallow straits and near-coastal zones with high resolution modeling.

3. MODELING

ADCIRC MODEL

Coastal areas are characterized by geometrically complex features which include bathymetry, rivers, channels, bays, wetlands and man made structures (dunes, levees, harbors and transport systems). Accurate modeling of hurricane or tsunami induced coastal flooding has been limited by the use of fixed size computational domains and the lack of sufficient clarity in the grid resolution. The fixed size computational domain limits the volume of water involved in the event. Grid resolution is important to capture the varying natural features such as bathymetry and coastal profile with man made structures and barriers. ADCIRC has a large domain-unstructured grid approach to compute hurricane and storm surge. The large domain allows the storm surge to naturally and accurately propagate from deep waters on to continental shelf and adjacent coastal region. The use of unstructured grid resolves important flow features on a localized basis, accurately solving the flow features on a localized basis. In order to develop proper and adequate coastal protection, it is critical to capture the flow features and transport of sediments as the storm surge propagates and recede thorough the Galveston bay and Houston Ship channel.

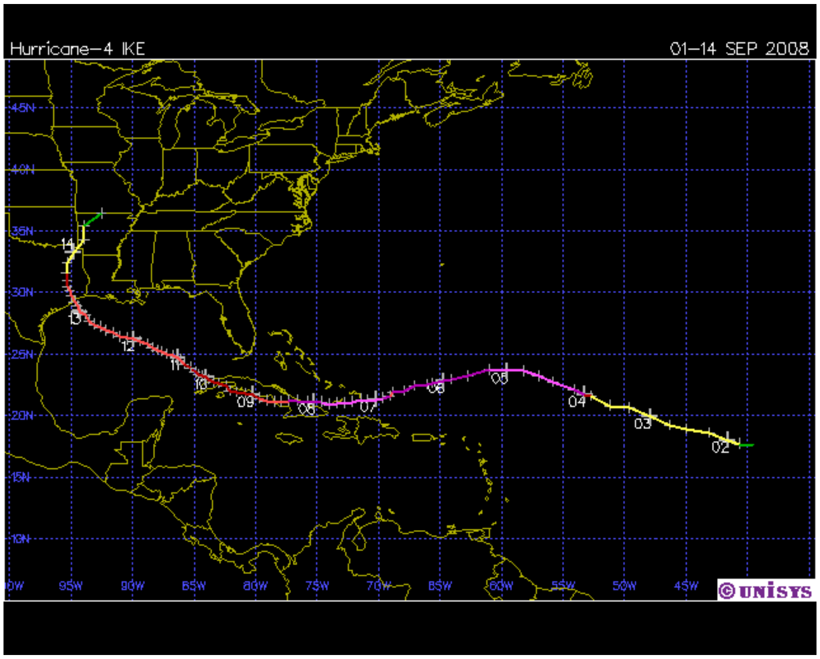

Figure 1. Hurricane IKE Pathway

LOCAL MODELING

The use of basin size domains with highly localized grid resolution significantly improves the predictive ability of computational models of hurricane storm serge in very complex flood plains.

ADCIRC-SMS MODEL CONTROLS

SMS is used to input the important parameters to the ADCIRC model. There are six different tabs that are used to input the data. The tabs include the following: (1) General, (2) Timing, (3) Files, (4) Tidal/Harmonics, (5) Wind and (6) Sediment options.
(1) General Tab: it includes the model, initial condition, Coriolis option (forces due to the latitude), solver type, number of iterations per time step, generalized properties (lateral viscosity) and bottom friction(for greater than 10 m use a value of 0.005 and for shallow water use a value of 0.02).

MODELING APPROACH

For this study of hurricane storm surge in the Gulf of Mexico around Galveston, two models with two different shoreline resolutions were created. The first model encompassed the domain between longitudes 93.0 W to 96.3 W and latitude 27.6 N and 30.0 N. (Fig. 2).

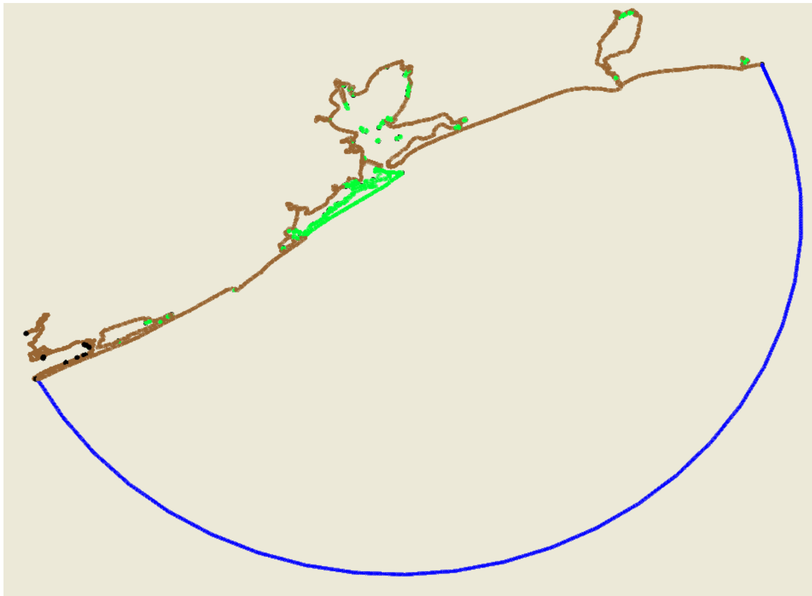

Figure 2: Model 1: Shoreline and ocean boundary.

The Model domain is considered relatively large. It was defined to check the global effect of the hurricane around Galveston. And model 2 was especially defined to investigate the effect of hurricane storm surge on Galveston and Houston ship channel precisely. ADCIRC two-dimensional depth integrated (2DDI) model was used and Surface Water Modeling System (SMS) is the preprocessing and post-processing software.

COASTLINE

The length of coastline was about 202 miles, about 8 times the size of the Galveston Island. It covers the region from Sabine Pass on the east side to Matagorda bay on the west side. The coastline data were imported from National Geographical Data Center (NGDC). The scale adopted was 1:250,000 and Houston ship channel was not captured in this model.

BATHYMETRY

The bathymetry data were also imported from National Geographical Data Center (NGDC). The resolution of the bathymetry data extracted can also be variable with a limitation on the maximum matrix of data that can be extracted at once. The bathymetry of model 1 has a resolution of 1 minute. The coastal area covered approximately 17,460 square miles.

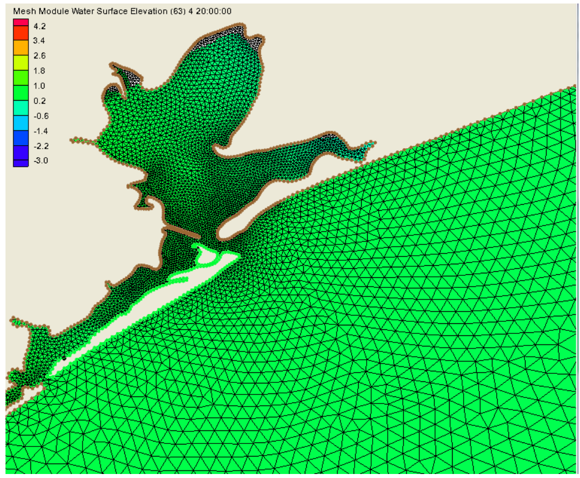

Figure 3. Meshing of the Coastal Region (Before hurricane)

FEM ANALYSIS

In the analysis section, with the ability of unstructured grid, the finite element mesh is generated to be fine around location of interest. The single meteorological wind forcing function is being used for the hurricane simulation. The models were run on University of Houston Texas Learning and Computation Center super computers. A total of 12,696 triangular elements were used to mesh the domain. The smallest and largest sides for the triangular elements were 500 m (0.31 miles) and 10,000 m (6.2 miles) respectively.

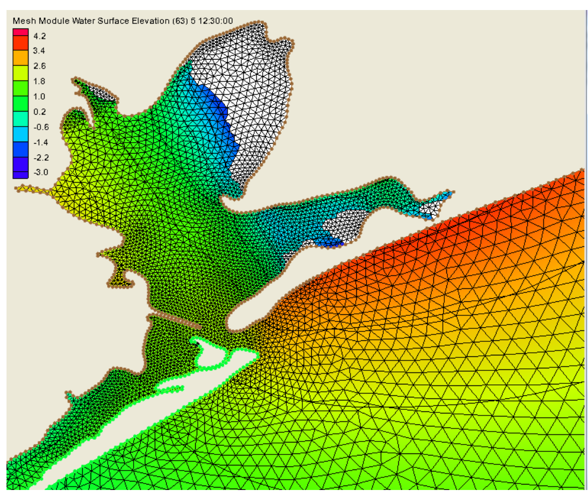

Figure 4. Storm Surge Bolivar Peninsula at Landfall of Hurricane IKE

RESULTS

The maximum storm surge recorded from the present simulation is 4.3 m (14.1 ft.) compared to the record of 15-20 ft as reported by the National Hurricane Center (NHC). (http://www.nhc.noaa.gov/surge/). It must be noted that there were some edge effects noted during the analyses.

4. SCALE EFFECT

When the scale was 1:70,000, the model clearly captures the Houston ship channel (Figure 5). It must be noted that the coastline that could be included in the model was only about 50 miles, compared to the earlier model where it was 202 miles. The coastal area covered was about 980 square miles compared to 17,460 square miles in the earlier case.

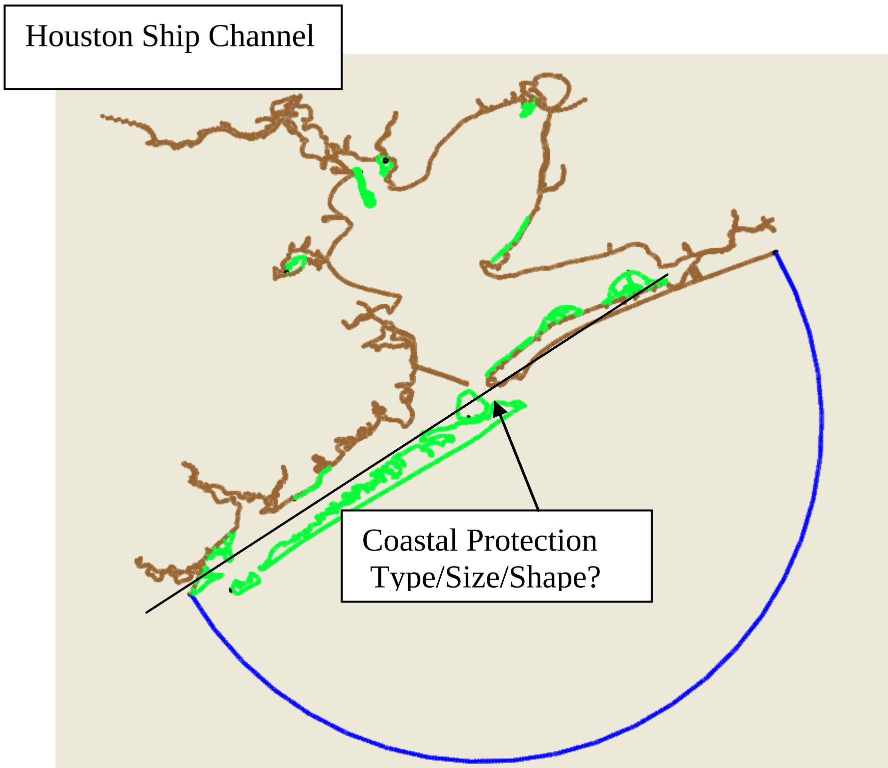

Figure 5: At a Scale of 1:70,000 Mapping of Galveston, Ship Channel and Coastal Protection

CONCLUSION

ADCIR was effective in predicting the strom surge caused by Hurricane IKE. Modeling required a super computer with over 100 processors. ADCIRC is a very useful numerical tool for an assessment of storm surge, but the effect of scale must be further investigated in order to evaluate the various coastal protection systems.

ACKNOWLEDGMENT

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