Hurricane Ike Field Investigation

A Report of Field Observations on October 3–6, 2008

Edited by

Billy Edge, Ph.D., P.E.

Lesley Ewing, P.E., D.CE

ASCE

COPRI

COASTS, OCEANS, PORTS AND RIVERS INSTITUTE

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Coasts, Oceans, Ports, and Rivers Institute of
the American Society of Civil Engineers

COASTS, OCEANS, PORTS & RIVERS INSTITUTE

Published by the American Society of Civil Engineers

Cataloging-in-Publication Data on file with the Library of Congress.

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia, 20191-4400
www.asce.org/pubs

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ISBN 978-0-7844-1120-9 (paper)
ISBN 978-0-7844-7688-8 (PDF)
Manufactured in the United States of America.

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Acknowledgments

The team is grateful to Paul Terrell of FEMA and John Lee of Galveston County for their help with access to restricted areas. Support for this study was provided by the ASCE and the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, and the Port and Airport Research Institute (PARI) of Japan. Permission was granted by the USACE Chief of Engineers to publish the contributions to this report authored by team members employed by the Corps of Engineers.

[1] Formerly Texas A&M University

In Memory

Dr. Donald Keith Stauble (1947-2009)

This report is dedicated to the memory of Dr. Don Stauble, a research scientist and coastal geomorphologist at the US Army Engineer Research and Development Center's (ERDC's) Coastal and Hydraulics Laboratory (CHL). Don was a significant contributor to the Hurricane Ike Field Investigation Team. His thoughtful insights to the coastal processes, identification of process signatures in the field and his detailed contribution to this report underscore his importance to this effort.

Don began his career with an appointment in the Department of Oceanography and Ocean Engineering at the Florida Institute of Technology from 1978 to 1987. In addition to educating students he conducted extensive research on the engineering aspects of beach restoration projects in Florida. The guidelines for these projects still remain a component of the current design guidance. In 1987, Don joined the Coastal Engineering Research Center (CERC) which later became CHL. Don's work at the CHL achieved national and international recognition for his research in coastal processes, inlets, response to hurricanes and tropical storms and management of coastal risks. His geomorphological interests extended from the Great Lakes to the Gulf coast to the outer limits of the United States. Don's expertise and contributions to the profession will continue to be shared through the students he has guided, his colleagues and his many scholarly publications. The words of Ms. Joan Pope, a colleague who worked for several years with Don at the CHL said what we all think about Don,

> *He was a quiet, kind, and gentle man, generally unflappable, and a good friend to all who might cross his path. When on the beach with shovel and sample bag in hand, Don would revert to an excited kid. He would collect samples and explain to any and all what they showed about this most complex of geological settings.*

Contents

Chapter 1: Introduction

Hurricane Ike made landfall at 2:10 a.m. on September 13, 2008, as a Category 2 hurricane. The eye of the hurricane crossed over the eastern end of Galveston Island, and a large region of the Texas and Louisiana coast experienced extreme winds, waves, and rising water levels, resulting in significant damage from overtopping, overwash, wind and wave forces, and flooding. Figure 1-1 shows the track of the storm and its location along this part of the coast. Major damage observed during the investigation was located between Freeport and Port Arthur, Texas. The effects of the hurricane force winds existed over thirty miles from the coast in Texas and Louisiana and the storm continued over land causing more damage and loss of life as it turned northeast and continued its 1,600-mile path of destruction across the United States.

The sustainability and resilience of engineering designs are continuously improved by reviewing the performance of existing designs and processes. The Board of Governors of the Coasts, Oceans, Ports and Rivers Institute of the American Society of Civil Engineers (COPRI of ASCE) recognized the opportunity to gain information from observing the performance of structures affected by Hurricane Ike. Three weeks after the storm, COPRI organized a field survey team to visit Galveston, Tex., and collect perishable data. The team received financial support from ASCE and worked in cooperation with the GEO Institute. This report provides a written record of observations and lessons learned for use by coastal, port, and civil engineers in future coastal development. COPRI has previously sponsored teams for similar assessments after Hurricane Katrina (ASCE 2006) and the 2004 Indian Ocean Tsunami (ASCE 2008).

The purpose of the Hurricane Ike field investigation was to survey, examine, document, and report the effects of Hurricane Ike on coastal landforms, buildings, coastal structures, infrastructure, marinas, and ports. Although COPRI intended to provide three field teams—one focusing on port facilities and the other two on coastal buildings, infrastructure, and processes—only the latter two were able to conduct their field investigations. The ports team was organized but could not gain access to the area ports to review and document damages.

The time available for the COPRI/GEO teams was limited, and many of the areas receiving extensive damage could not be covered in this short time. For example, the Bob Hall Pier at Corpus Christi, Tex., well to the south of the eye of the storm, experienced extensive damage. Additionally, areas that survived well, such as the levees along the Sabine River, were not observed, but their safety was noted.

Observations

On October 3, 2008, the two COPRI coastal field teams assembled in Galveston for four days of coastal investigations. The teams collected perishable data, made observations, and documented conditions. The coastal teams focused on beaches, small buildings, marinas, shoreline structures, bridges, and other civil infrastructure. The teams covered the Texas coastal areas as far east as Sabine, including Bridge City, and as far west as Surfside Beach. The teams also made observations on the western side of Galveston Bay. The survey area is shown in Figure 1-1and includes coastal areas on both sides of the hurricane path. Communities both east and west of the eye had significant damage.

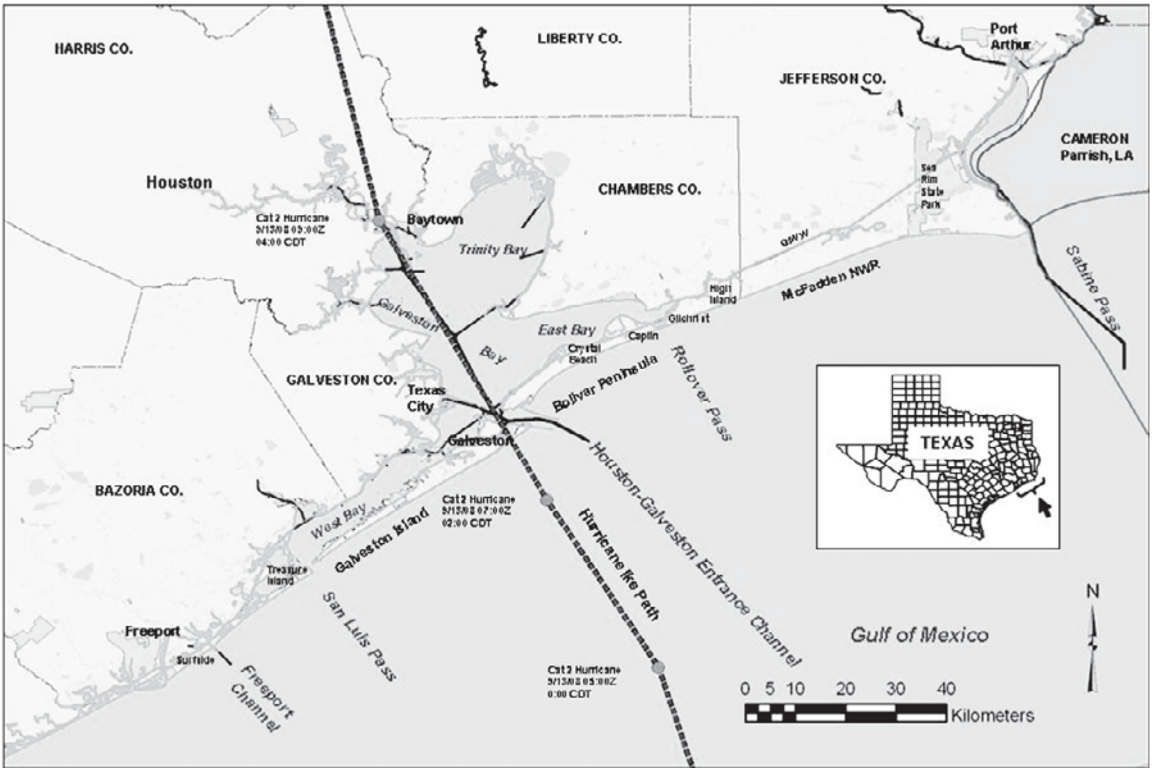


Figure 1-1. Location map of upper Texas coast impacted by Hurricane Ike, showing the hurricane path and points from National Hurricane Center

Scour was apparent throughout most of the damage areas, and floating and wind-blown debris was broadly spread. Large overwash fans were often observed inland of the first row of houses and the seaward road. Beach and dune systems were highly eroded, with flattened or significantly deflated dunes. Utilities and infrastructure exhibited extensive damage, water and sewer lines were broken, roads were undermined or buried in sand and debris, and telephone and electric lines had collapsed. Community water towers appeared to be undamaged. The well-built floating docks observed were undamaged, except for one dock area in a covered boat shed. Older fixed-pier systems typically suffered more damage. Much of the damage to small commercial and pleasure craft was observed at these older fixed-pier systems.

There was a broad variety of building types in the storm area—ranging from older slab-on-grade development and elevated buildings built to early flood standards to those meeting current flood standards and a significant number of above-standard or "fortified" homes. With a few exceptions where conditions exceeded the design standards, structures built to current or fortified standards performed fairly well. For Hurricane Ike, elevation seems to be the main factor for building defense. Many of the surviving buildings had deep piles, and the main living area was above wave height. Breakaway walls and lower-level stairs detached from the main building and functioned as expected. Slab foundations had extensive damage. Pile foundation failure was observed from inadequate pile penetration, design defects, and wave forces. On both Bolivar Peninsula and Galveston Island, the survey teams were able to identify the high-water level from marks on buildings and piles or from debris lines. Watermarks on fixed structures were noted, elevations were estimated, and coordinates were recorded. Perishable data were collected and subsequent Federal Emergency Management Agency (FEMA) teams or LIDAR efforts were able to survey these locations and establish geodetically referenced water levels that can be used to calibrate surge models and to update flood elevations.

Galveston Island and Bolivar Peninsula had installed a range of shore protection projects prior to Ike. Some of these protective efforts survived the hurricane and protected inland development. However, the gulf shore protection was not effective against the surge and flooding that came from the bay side. As with buildings, much of the effectiveness of the shore protection depended on elevation. Low revetments and groins were overtopped, and some 3 to 5 ton stones were displaced. Geotextile barriers were overtopped, and some tubes rolled either seaward or landward of their apron or underlayer. Once the tubes are displaced from their foundation, they tended to flatten and be fully or partly buried in sand. Beach survey data for this coastal region were acquired in 2003 and again in 2008 via LIDAR.

According to the Texas General Land Office, initial estimates indicated that there were approximately 3,600 significantly damaged (greater than 50 percent) or destroyed upland structures. On Galveston Island, approximately 1,261 structures were significantly damaged or destroyed.

Surveys by Others

The Bureau of Economic Geology at the University of Texas (TxBEG) has documented the shoreline area of the upper Texas Coast for many years through profile surveys, aerial photographs, and LIDAR. Survey data are available from 1957, 1974, 1982, 1995, 2000, 2001, 2002, 2006, and 2008, providing information on long-term shoreline change. The more recent 2006 and post-hurricane surveys provided information that was used to examine storm-induced coastal changes. Additional post-storm surveys have been undertaken or are being planned by the National Oceanic and Atmospheric Administration (NOAA), the Joint Airborne Lidar Bathymetry Technical Center of Expertise (*JALBTCX*), and the Texas General Land Office. Post-Ike aerial photograph was made available by NOAA. These data will be analyzed in further studies by FEMA and the USGS and comparison with previous survey data will allow some analysis of the erosion protection provided by the array of shore protection measures.

FEMA is the lead federal agency in identifying the major damages and assessing the impacts to communities from events such as Hurricane Ike. In December 2008, FEMA published *Hurricane Ike, Impact Report*. FEMA estimates that Hurricane Ike caused approximately $3.4 billion in housing damages, $1.7 billion in water and wastewater plant damages, $131.8 million in damages to roads, and approximately $2.4 billion in repairs to navigable waterways, ports, and coastlines (FEMA 2008). Approximately one month after the FEMA report, a report on state and local government responses to the hurricane and issues to prepare for future natural disasters was submitted to the Texas House of Representatives by the House Select Committee on Hurricane Ike Devastation to the Texas Gulf Coast. During the following months, analysis of the storm data and examination of the impacts on the coastal area continued. The data and information acquired by the COPRI field investigation was analyzed and put into context with other available surveys and studies. The significance of various observations was assessed, and material from the investigation teams was condensed into this field assessment and “lessons learned” report.

Other Reports

A number of individual investigations were conducted by various sources, including the U.S. Army Corps of Engineers (USACE) District Office in Galveston and state and county consultants. Several of these studies were reported in the spring 2009 issue of *Shore and Beach.*

Kraus and Lin (2009) documented the severe damage to the coastline and provided some observations of damage to structures on the west end of Galveston Island. A detailed review of the damages on the Bolivar Peninsula was provided by McLellan and Lee (2009). Their surveys indicated that more than 80 percent of all structures on the peninsula received some damage, and about 44 percent were destroyed. The effect of Ike was felt as far away as South Padre Island, which experienced significant erosion due to a surge of only 1 meter (Heise et al. 2009). Tirpak (2009) provided an overview of the operational experiences during and immediately after the storm and USACE's responses to Hurricane Ike. Williams et al. (2009) discussed the ecosystem impacts of Hurricane Ike and suggested major themes for identifying critical areas for future research and science-based management to provide long-term stability to barrier ecosystems. Each of these papers provides valuable additional information to this report.

The Team

Team members had expertise in sediment dynamics, wave run-up, surge, scour, small structure damage assessment, hydrodynamics, coastal engineering, coastal design, geomorphology, and geotechnical engineering. Several team members had experience on previous disaster survey teams.

The following lists participants on the two coastal teams:

Billy Edge, Texas A&M—Team Leader
Spencer Rogers, North Carolina Sea Grant— Team Leader
Robert G. Dean, University of Florida
James Kaihatu, Texas A&M
Lesley Ewing, California Coastal Commission
Mandy Loeffler, Moffatt & Nichol, Houston
Margery Overton, North Carolina State University
Kojiro Suzuki, Port and Airport Research Institute, Japan
Paul Work, Georgia Tech
Garry Gregory, Gregory Geotechnical—ASCE Geo Institute Liaison
Donald Stauble, USACE/ERDC/CHL
Jeffrey Waters, USACE/ERDC/CHL
Eddie Wiggins, USACE/JALBTCX
Marie Horgan Garrett, Coastal Solutions, Inc.

The first 10 individuals listed are ASCE members. Dr. Suzuki's participation was sponsored by the Port and Airport Research Institute of Japan. USACE supported the participation of Don Stauble, Jeff Waters, and Eddie Wiggins. Additionally, Marie Garrett, a local citizen who volunteered her support and knowledge, provided much useful information. The field survey efforts would not have been possible without the support and assistance of the many people who helped the teams gain access to restricted areas and arranged food, lodging, transportation, and other logistics.

Chapter 2: Setting

Galveston Area

Galveston Island, a low-lying barrier island on the upper Texas Gulf coast, is in the center of the survey region and is the economic focus of the coastal area. Approximately 48 km long and 0.8 to 1.2 km wide, the island separates the Houston metropolitan area and the Galveston Bay system from the Gulf of Mexico, as shown in Figure 2-1. The densest areas of the city of Galveston are located at the northern tip of the island, approximately 72 km southeast of downtown Houston. This section of Galveston Island, known as East Beach, is protected by a seawall with a crest elevation ranging from 4.7 to 5.2 m above MSL that was built after the Galveston Storm of 1900. The remainder of the island outside the seawall, known as West Beach and shown in Figure 2-1, has been developed as a series of small beach subdivisions and Galveston Island State Park.

To the north of Galveston Island is the Galveston Bay system, which includes Galveston, Trinity, and East and West Bays (Figure 1-1). Bolivar Peninsula, east of Galveston Island, is a narrow strip of land in Galveston County separating East Bay from the Gulf of Mexico. Similar to Galveston Island, Bolivar Peninsula is comprised of several small beach villages, including Crystal Beach, Caplen, Gilchrist, and High Island. The Galveston area is home to several important navigation channels, including the Houston Ship Channel, the Texas City Ship Channel, the Galveston Navigational Channel, and the Gulf Intracoastal Waterway (GIWW).

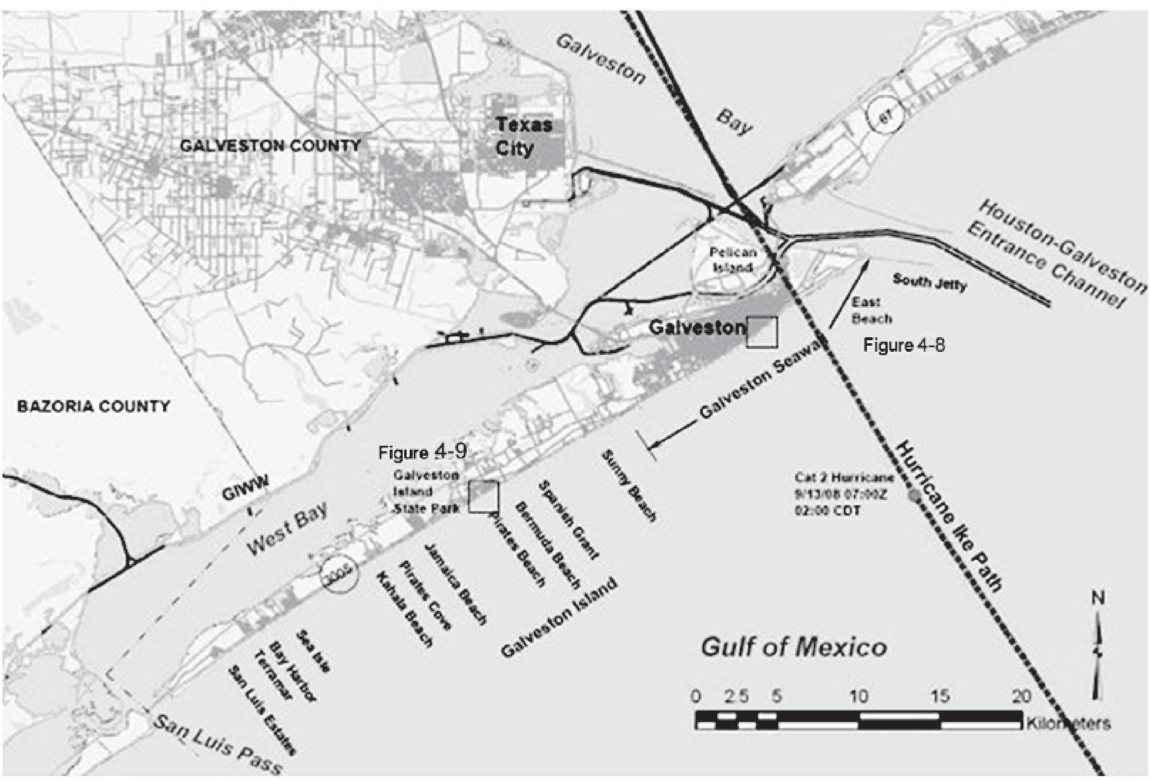


Figure 2-1. Galveston Island location map. Boxes show location of Figure 4-8 and 4-9

Freeport is located in Brazoria County, approximately 65 km southwest of Galveston. Freeport is separated by the GIWW from the towns of Surfside and Quintana, which flank the north and south sides of the Freeport Channel jetties.

The Beaumont-Port Arthur, Tex., area is located in Jefferson County, approximately 105 km northeast of Galveston along the border between Texas and Louisiana. This area was on the onshore wind side of the storm track and is shown in Figure 2-2.

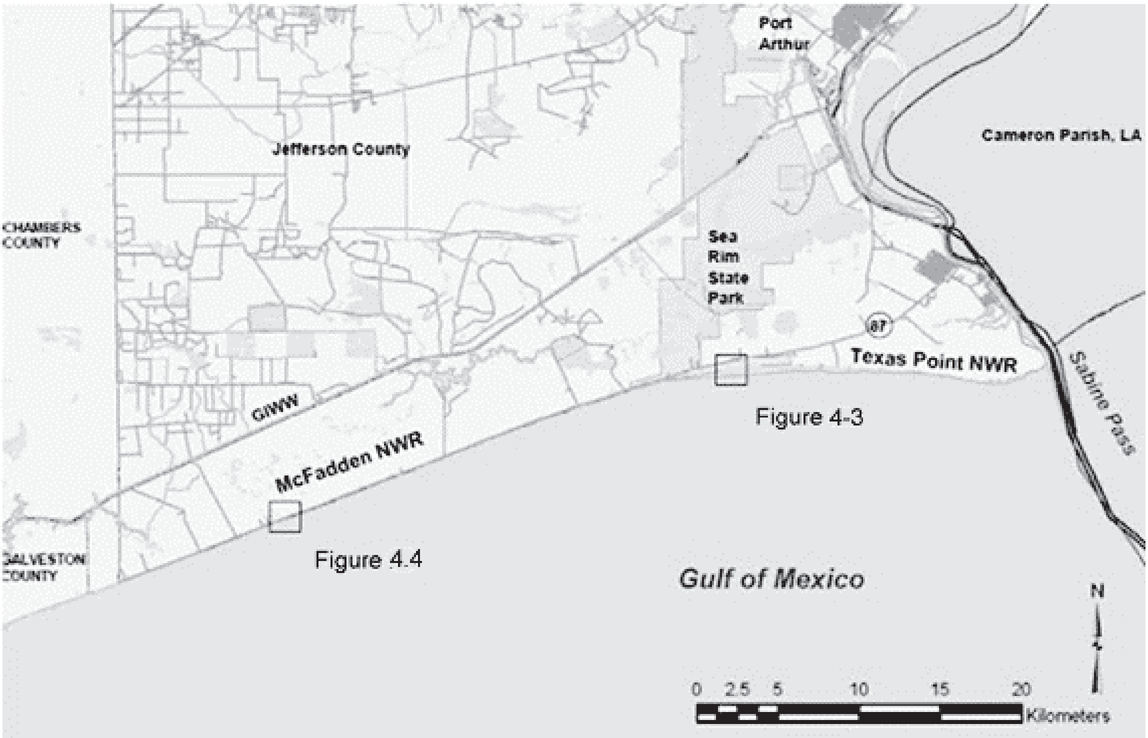


Figure 2-2. Location of the Jefferson County deltaic headland coast. Boxes show location of Figures 4-3 and 4-4

Geology

The investigation area is comprised of four distinct geomorphic regions: (1) the thin barrier beach sands overlying the Pleistocene headland (Beaumont Formation) from the Sabine Pass to High Island; (2) the Bolivar Peninsula, a beach ridge system developed by spit accretion; (3) Galveston Island, an extensively studied progradational barrier island; and (4) the barrier beaches of the Brazos River Holocene headland from San Luis Pass to the Freeport Channel. Variations in the evolution of these four geomorphic regions are due primarily to differences in antecedent geology and sand supply.

During the last glacial maximum approximately 20,000 BP[1], sea level was nearly 350 feet below its present level, and the east Texas shoreline was some 80 miles seaward of its current position (Anderson 2007). During this sea-level lowstand, the Brazos, Trinity, and Sabine rivers carved

[1] 20,000 years before present is commonly used in referencing geologic time scales.

deep channels in the underlying Pleistocene surface and formed large deltas at the base of the continental slope (Anderson et al. 1996). Sea level started to rise about 18,000 BP, and the rate of sea-level rise was greatest between 14,000 and 5,000 years ago. The rate of rise slowed dramatically approximately 5,000 BP, allowing the evolution of the modern Texas shoreface. Throughout this period, the rate of sea-level rise was variable, and at times, the shoreline migrated landward several miles within a few centuries (Rodriguez et al. 2004).

During the Holocene sea-level rise, the sediment loads of the Brazos, Trinity, and Sabine river systems were very different. The sediment load of the Brazos River was sufficiently large that the river completely filled its deep river valley and developed a delta on the modern shoreface. However, the Trinity and Sabine River systems carried much lower sediment loads, which were insufficient to completely backfill their valleys. Rising sea levels drowned these river valleys producing Galveston Bay and Sabine Lake. The modern Trinity and Sabine rivers deposit their very limited coarse grain load as bay-head deltas in upper Trinity Bay and upper Sabine Lake. As a result during at least the last 5,000 years, no sand has been delivered to the Texas Coast between Sabine Pass and San Luis Pass by the Trinity or Sabine fluvial systems. The limited sand found on the modern beaches between Sabine and San Luis passes represents ancestral riverine deposits and shoreface material that has been reworked with the rising Holocene sea level.

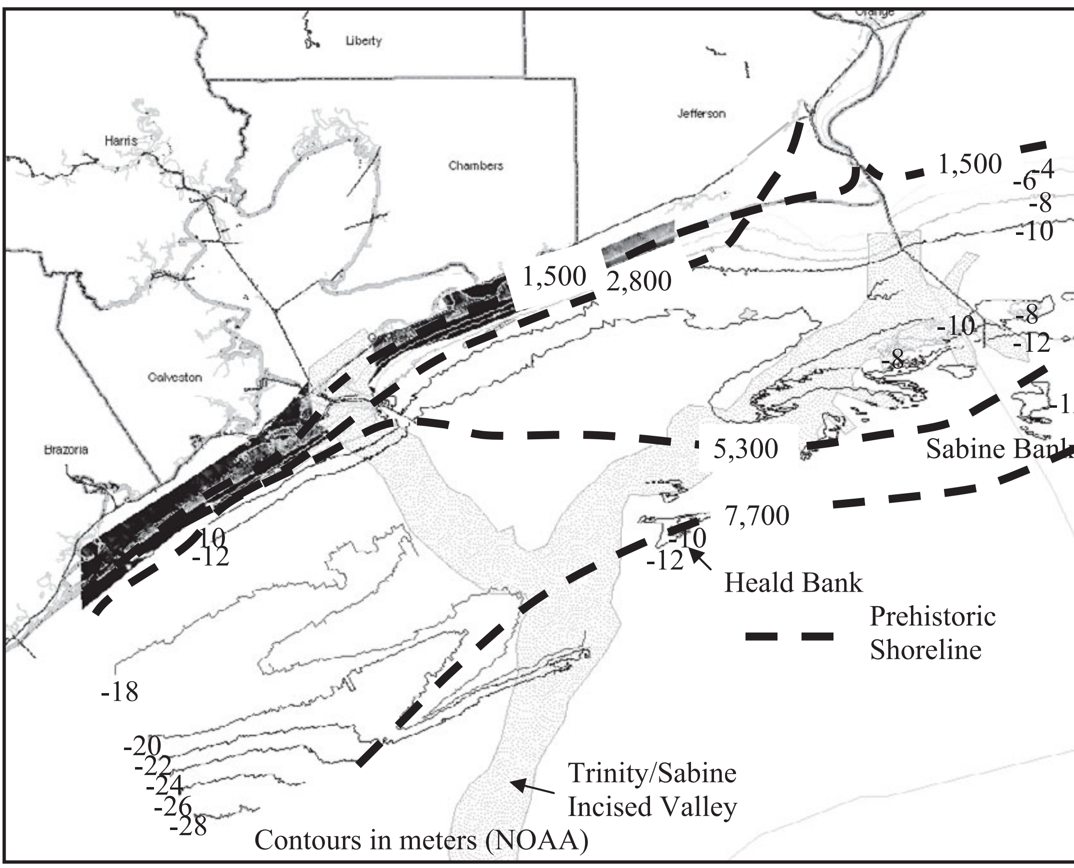


Figure 2-3. Study area showing the approximate locations of pre-historic shoreline positions for 7,700, 5,300, 2,800, and 1,500 years ago. Modified from Rodriquez et al. 2004

Galveston Island is one of the most extensively studied barrier islands in the world, and its geomorphic evolution is well established. Galveston Island has been cited as a typical example of a progradational barrier island (Morton 1994). Progradational barriers form as a result of relative sea-level stability and abundant alongshore and offshore sand supply. Galveston Island began to form approximately 5,500 years ago and accreted seaward by the addition of sand that was transported from offshore (Anderson 2007). This accretionary process combined with aeolian sand transport produced the modern landscape, which consists of a series of ridges and swales. Sand is not currently being delivered to Galveston Island by either alongshore or offshore transport processes; thus, the island is currently in an erosional phase. The youngest beach ridges on the east end of Galveston Island are approximately 1,800 years old, and younger ridges have been eroded by the advancing shoreline (Anderson 2007). Additionally, radiocarbon dating of shell material found in the marine mud deposited on top of the erosional surface at the base of the shoreface offshore of Galveston Island indicate that the transition from accretion to erosion occurred about 1,200 years ago (Rodriguez 2001). The exception to this erosional condition occurs at East Beach where sand has been transported east by littoral currents and accreted adjacent to the south jetty.

When Galveston Island was beginning to form, the East Texas shoreline was located at the approximate position of the modern Sabine Bank (Figure 2-3). Drill core deposits sampled and dated by Rodriguez et al. (2004) just offshore of the Bolivar Peninsula indicate that the East Bay extended seaward of its current location and that a barrier shoreline existed seaward of Bolivar Peninsula from at least 7,700 to 1,500 years ago. Rodriguez et al. examined 260 cores, four sand-quarry exposures, and 83 radiocarbon dates from these samples. Their well-constrained reconstruction indicates that a 40-km-wide middle Holocene estuary on the eastern side of the Trinity incised valley was protected from marine influence by a barrier shoreline located near Sabine Bank. The barrier shoreline retreated to a position just offshore of Bolivar Peninsula by approximately 2,800 BP. Bolivar Peninsula itself began to form about 1,500 years ago, and it grew by spit accretion with the lateral accretion of sand layers from the west directing alongshore currents that transported sand along the coast to form a spit. The rate of lateral accretion slowed as the western end of the spit encountered the old Trinity River valley because of the greater volumes of sand required to fill the valley (Anderson 2007).

The eastern Texas coastal system from Sabine Pass to High Island is a region of marginal deltaic sedimentation that is transitional to the prodelta deposits of the Mississippi River to the east and the transgressive/regressive barrier beach and barrier island systems to the west (Penland and Suter 1989). In easternmost Texas and western Louisiana, marginal deltaic sedimentation reflects regional-scale westward littoral drift and the deposition of fine-grained sediments as mudflats (Osborne and Worsham 2003). Holocene channel switching of the main stem of the Mississippi River accommodated periods of reduced mudflat deposition that, in turn, promoted the development of sand beaches through wave erosion and reworking. This easternmost section is the chenier plain that is characterized by a broad salt marsh having a muddy substrate (Morton 1997). Beaches in this section are narrow and steep and are composed of mud or a thin veneer of sand and shell over mud. West of the chenier ridges, Sea Rim State Park is an anomalous sandy beach that has been attributed to sand derived locally from underlying Pleistocene river deposits (Morton 1975) and/or the convergence of littoral cells. The shoreface of the McFadden Wildlife Refuge extends from the Sea Rim State Park to High Island and consists of a headland composed of late Pleistocene fluvial-deltaic deposits. Beaches of this Pleistocene headland are narrow and are often covered by shell pads that migrate along the beach depending on wave heights and sediment transport directions. Foreshore beaches are steep and berm crests are well defined where thick shell pads are present.

The western portion of the study area occurs within the Brazos Delta plain. The Brazos River delivers more sediment to the coast than any other Texas river (Anderson 2007). However, in 1929, USACE altered the course of the Brazos River by dredging a new channel to a location 6 miles west of the old river mouth. The diversion of the Brazos River has resulted in the complete deflation of the Brazos Delta at Surfside Beach and accelerated shoreline erosion rates. The presence of large sand dunes in eastern Surfside Beach is the result of locally derived sand from an ancestral channel of the Brazos River (Anderson 2007).

General Elevation Characteristics

Variation of elevation of the coast from Freeport to Sabine is very limited with only small dunes providing relief. Many areas are flat with a berm-fronting marsh, and in other areas, development extends to the edge of the vegetation line with nearly no relief. Toward the west end of Galveston Island, there are a few small dunes up to 2 m elevation. The other dunes are artificially created using geotextile tubes with a sand veneer. The topography of Galveston is shown in Figure 2-4. Elevations above 2 m behind the seawall are the result of the raising of the island after the 1900 hurricane. The areas higher than 7.5 m are typically confined disposal sites for dredged material.

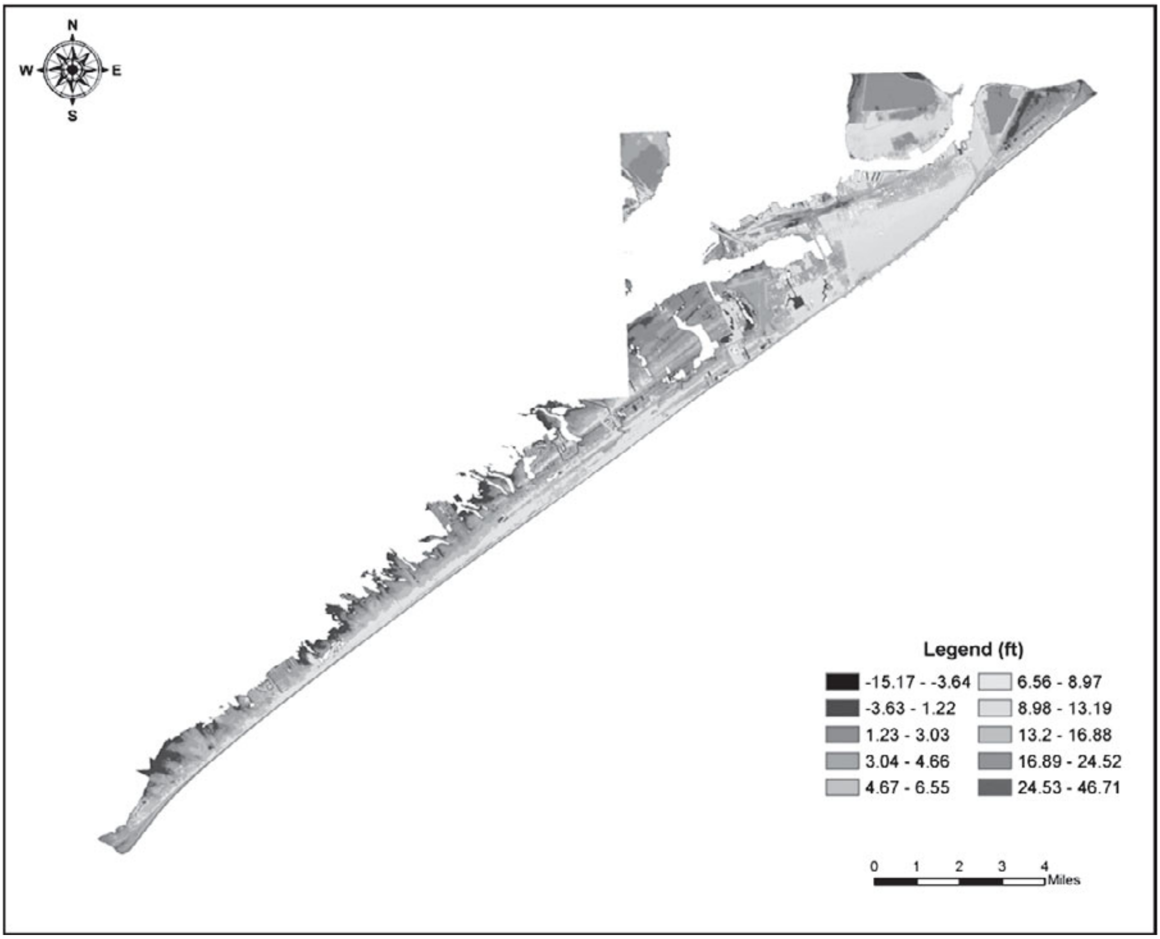


Figure 2-4. Elevation in feet of Galveston Island in National Geodetic Vertical Datum (NAVD) 1988

Galveston Storm of 1900

At the turn of the 20th century, Galveston was the fourth largest city in the state of Texas with a population of 37,000. Economically prosperous and cosmopolitan, the city was nicknamed the "Wall Street of the Southwest." However, the prosperity and grandeur of Galveston forever changed course on September 8, 1900, when a Category 4 hurricane with winds estimated at 140 mph and a maximum storm surge of 4.8 m mean sea level (MSL) deluged Galveston, which at the time measured 2.7 m MSL at its highest point. The surge and pounding waves left in its wake between 6,000 and 8,000 people dead and 3,600 buildings destroyed. Referred to as the Storm of 1900, this storm remains the deadliest natural disaster in U.S. history.

Galveston Seawall, Grade Raising, and Groins

In September 1901 approximately one year after the Storm of 1900, the Texas State Legislature approved an act for the construction of a seawall on Galveston Island to prevent destruction from future storms. A board comprised of three engineers, Brigadier General Henry Martyn Robert, Alfred Noble, and H. C. Ripley, organized draft plans for the construction of a 4.8-km-long, 5.2-m-high, concrete gravity seawall along the seaward side of the island (Wiegel 1991). The seawall was concave in shape with its upper portion vertical to deflect large ocean waves upward and to limit overwash into the city. The initial segment of the seawall originated near the south jetty and extended westward to 39th Street. Construction commenced in the fall of 1902 and was completed in July 1904. A second segment measuring 1,524 m was constructed between December 1904 and October 1905 to protect Fort Crockett. This segment ran from 39th to 53rd streets. A third segment of 548 m was added in 1926 and 1927. The fourth and final extension of the seawall to 61st Street was completed in 1963, bringing the total length of the seawall to 16 km (Hansen 2007).

Following the initial completion of the seawall, engineers proposed raising Galveston's elevation to protect the remainder of the city from damaging storm surge and waves. The original elevation of Galveston Island averaged less than 1 m. Approximately 9.2 million m^3 of fill was used to raise the city to 5.1 m near the seawall, sloping to 2.4 m throughout most of the residential areas. The project used fill material dredged from between the jetties at the entrance of Galveston Harbor. The primary challenges included lifting more than 2,000 buildings, as well as sewer, water, and gas mains without breakage or service interruption. The grade raising was completed in August 1910.

Construction of the seawall did not prevent erosion of the sand beach fronting the structure and protecting the toe of the seawall. In the mid-1930s, an effort was initiated to construct a series of groins to retain the sand in front of the seawall (Hansen 2007). From 1936 to 1939, a series of 13 steel sheet pile groins were constructed from 12th to 55th streets. The groins measured 152 m in length and were spaced 457 m apart. The groins were later rehabilitated in 1968 to include stone, and two additional groins were built to create the current groin field with 15 structures.

1995 Beach Nourishment

In late May of 1995, the City of Galveston completed a beach nourishment project of the beaches within the groin field fronting the seawall. The purpose of the project was not storm protection but rather enhancing recreation and tourism. Approximately 542,000 m^3 of sand was placed within the 5.8-km project area. Nourishment material was dredged from a sand source approximately 2.4 km offshore of East Beach near the west jetty.

Smaller nourishment projects of about 53,000 m^3 each were completed in 1998, 1999, and 2000. Material for the nourishments was obtained by scraping accreting material east of the west jetty and trucking the sand to the placement area in front of the seawall.

Coastal Processes

The coastal processes affecting the upper Texas coastline include changes in relative sea level, water levels, wind-induced waves and currents, and sediment transport. Relative sea-level rise is measured at 6.8 mm per year based on monthly mean sea level data from 1957 to 2006 at the Galveston Pleasure Pier, which is equivalent to a difference of 0.68 m in 100 years (NOAA 2008). Any increase in sea-level rise tends to cause both a landward translation of the beach profile and an increase in nearshore wave heights, which can result in significant shoreline recession. The relatively flat beach and offshore slope amplifies the impact.

The water levels in the Galveston area are influenced by tidal processes in the Gulf of Mexico, freshwater inflows from rivers (particularly greater Galveston Bay), local wind speed and direction, and tropical and extra-tropical storm events. Water-level elevations relative to National Geodetic Vertical Datum (NAVD) 88 are based on the tidal station 877 1510 TIDAL 43 at the Galveston Pleasure Pier station (#8770570), as shown in Table 2-1. Tides are typically diurnal with a tidal range of 0.62 m between mean high higher water (MHHW) and mean low lower water (MLLW).

Table 2-1. Tidal Datum in Meters Relative to NAVD88 (Galveston Pleasure Pier, #8771510)

Tidal Datum	Galveston Pleasure Pier (#8771510)
MHHW	0.436
MSL	0.152
NAVD88	0.00
MLLW	-0.186

Tropical storms and hurricanes can either increase or decrease the water level depending on the relative location of the storm and the local storm surge. Cold fronts produce a temporary increase in water levels due to wind setup as the wind blows from the southeast prior to the passage of the cold front. This is a particularly noticeable event for every front passing through Galveston Bay.

The northeast end of Galveston Island is adjacent to the entrance of Galveston Bay and the Galveston-Houston ship channels. Two rock jetties are located on either side of the channel. The west jetty, approximately 6.0 km in length, is adjacent to East Beach. The east jetty is located on the eastern tip of Bolivar Peninsula and is approximately 7.64 km in length. Southerly winds during the summer produce a northeasterly littoral drift, which is trapped by the south jetty and leads to historic accretion on East Beach. During the remainder of the year, easterly winds predominate producing a southwesterly littoral drift. This littoral transport direction is dominant for Galveston Island and Bolivar Peninsula, with the north jetty similarly trapping material on its adjacent beach.

Historic shoreline change rates and directions along the Texas Gulf Coast is computed by the University of Texas Bureau of Economic Geology (TxBEG) by comparing shoreline position from the 1930s with those from the 2000s and applying a linear model. The results are expressed as average annual rates of change (Gibeaut 2004). BEG shoreline change calculations indicate average annual erosion rates of about +1.2 to +2.65 m per year (m/yr) on East Beach. Moderate accretion and recession occurs along the shoreline fronted by the seawall with rates ranging from approximately +1 to -0.2 m/yr, with areas of higher accretion rates due to beach nourishment activities. Immediately west of the termination of the seawall, recession rates for Galveston Island are highest at -3 to -3.3 m/yr. Rates somewhat decrease to an average of -1 to -2.1 m/yr along the remainder of the island. On Bolivar Peninsula, up to approximately 6.4 km of the shoreline to the east of the jetty is accreting, with rates up to +6.1 m/yr closest to the jetty. Erosion rates vary between -0.6 to -2.1 m/yr up to High Island (BEG 2008).

Dunes on Galveston Island are small and seldom exceed a height of 1.8 m NAVD. The dunes on Bolivar Peninsula are similar to those in Jefferson County. Some Jefferson County locations have no dunes fronting approximately 22.5 km of state and federal wetlands. In other areas, the maximum elevation is approximately 1 m NAVD.

Chapter 3: Hurricane Ike

Hurricane Ike formed from a tropical wave that moved off the coast of West Africa on August 28, 2008. It became a tropical depression on September 1 in the Atlantic basin some 2,400 km east of the Leeward Islands. The storm moved west northwest over the tropical Atlantic Ocean and rapidly intensified to a tropical storm within a day (Figure 3-1). By September 3, Ike was a Category 1 hurricane. Later that day, it had grown to a Category 4 storm and the next day reached a peak wind intensity of 65 m/s (126 kts). Ike weakened to a Category 2 storm as it progressed west southwestward on September 5 and 6. As Ike approached the Turks and Caicos and the southern Bahamas on September 7, it re-strengthened to a Category 4 storm. On September 8, Ike made landfall on the northeast coast of Cuba with maximum sustained winds about 56 m/s. The storm moved over Cuba and re-emerged off the south coast later that day. The storm paralleled the south coast of Cuba with Category 1 wind intensity. A second landfall on the southeast Cuban coast occurred on September 9, and the storm track moved northwest back out over water into the gulf. For three days the storm progressed northwestward through the Gulf of Mexico, with intensification from a Category 1 to a Category 2 storm. Ike made its U.S. landfall over the northeastern end of Galveston Island about 2:10 a.m. CDT on September 13, maintaining its strength as a Category 2 storm. Maximum sustained winds were reported by NOAA, the National Weather Service, and the National Hurricane Center at 49 m/s. As the storm moved up Galveston Bay, almost paralleling the Houston Ship Channel, it maintained its Category 2 status. It began to weaken, first to a Category 1 hurricane and finally a tropical storm as it moved over eastern Texas and into Arkansas. It moved up the Ohio and Mississippi valleys and became extratropical as it dissipated over Lake Huron and moved into Canada on September 15.

At landfall the storm was moving to the northwest at 8.6 kts, and the sustained wind speed was reported as 49 m/s, making Ike a strong Category 2 storm (National Hurricane Center archived reports). Hurricane strength winds extended up to 190 km from the center of the storm, with tropical storm force winds to 440 km (Figure 3-2).

The storm resulted in damages over a large section of the coast of Texas, including Surfside Beach, Galveston Island, and the Bolivar Peninsula in particular. Damages resulted from high winds, storm surge, wind waves superimposed on top of the storm surge, and scour and sediment transport, which in some cases led to failure of residential structures and infrastructure, such as roads. The conditions that led to these damages are described in the following sections.

Water Levels

NOAA maintains several stations for measurement of winds and water levels in the area (Figure 3-3). Several of the water-level sensors failed as water levels increased during the storm; thus, the peak storm surge was not recorded. In some instances, backup systems recorded data throughout the storm. Results discussed here are based on preliminary data. Subsequent watermark surveys conducted by FEMA, the state, and others, including members of the ASCE site visit team, will increase the knowledge of the water levels during the storm.

The U.S. Geological Survey (USGS) installed temporary storm surge gauges immediately before Hurricane Ike reached landfall. Many of the gauges were recovered and provide valuable hydrographs. Some even have a wave signature. Each gauge was accompanied by an atmospheric pressure sensor for calibration of the subaqueous pressure sensors.

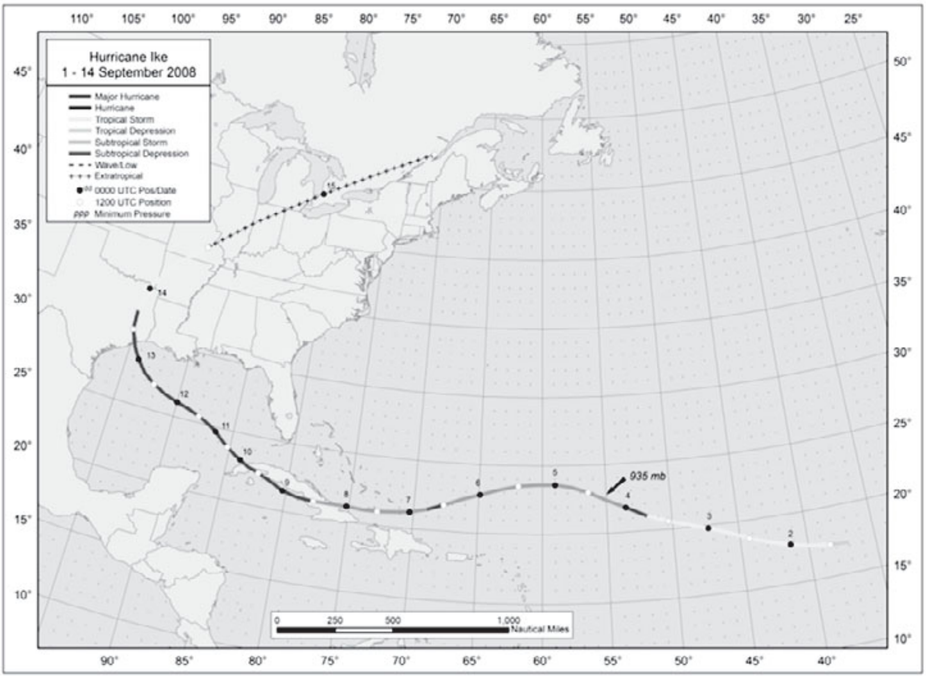


Figure 3-1. Best track positions for Hurricane Ike, September 1-14, 2008. Track during the extratropical stage is based on analyses from the NOAA Hydro-Meteorological Prediction Center and Environment Canada. Source: Berg (2008)

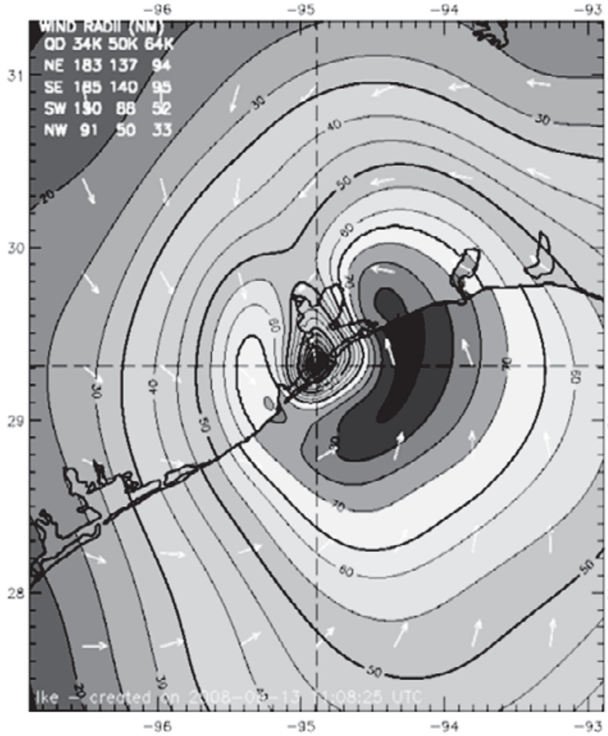


Figure 3-2. Wind field at 7:30 a.m. on September 13, 2008, as Hurricane Ike made landfall near Galveston. (Wind speed is in kts.) Source: NOAA Hurricane Research Division

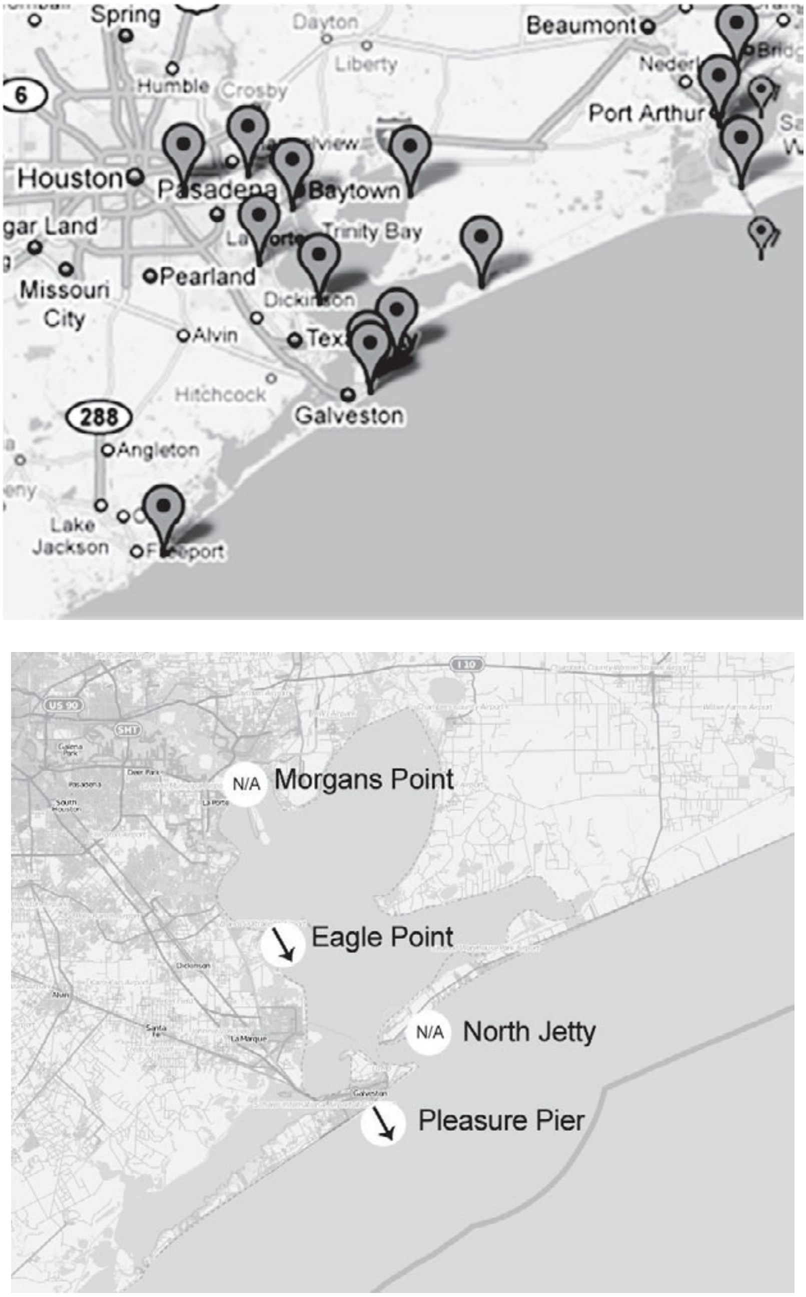


Figure 3-3. Locations of NOAA water-level and meteorological data collection stations in Galveston area

Tides in the area are diurnal, with a mean range of 0.44 m on the gulf side of Galveston Island (Pleasure Pier/Flagship Hotel). The NOAA tide gauge on Galveston Island's Pleasure Pier reported a maximum 6-minute water level of 3.55 m NAVD88 (5:30 a.m. September 13, 2008) and a maximum storm surge (defined here as measured mean water level minus predicted mean water level) of 3.29 m, also at 5:30 a.m. This exceeds the previous historical maximum water level for this station of 2.62 m NAVD88, recorded on September 11, 1961 (Hurricane Carla).

At the entrance to Galveston Bay, mean water level peaked at 2.75 m NAVD88 at 1:12 a.m. on September 13 before the gauge failed. This corresponds to a storm surge of 2.87 m, but both the tide level and storm surge were still rising when the gauge failed.

The tide range within Sabine Pass is slightly less than at Galveston Pleasure Pier, with a mean range of 0.32 m. This gauge survived the storm, reporting a maximum water level of 5.39 m NAVD88 at 8:00 a.m. on September 13, 2008 (Figure 3-4).

The tide gauge at Freeport, west of Galveston Island, also survived the storm and displays two interesting characteristics (Figure 3-4). This station, located 40 km west of the eye of the storm's landfall, experienced strong offshore winds as the storm came ashore. The storm surge peaked prior to landfall, earlier (late on September 12) than at the other locations in the area, and displays a secondary maximum on September 14 that is also evident at Sabine Pass. Measured hydrographs for each station in the area that provided usable data are provided in the appendix. Maximum values of water level, storm surge, and meteorological parameters are reported in Table 3-1.

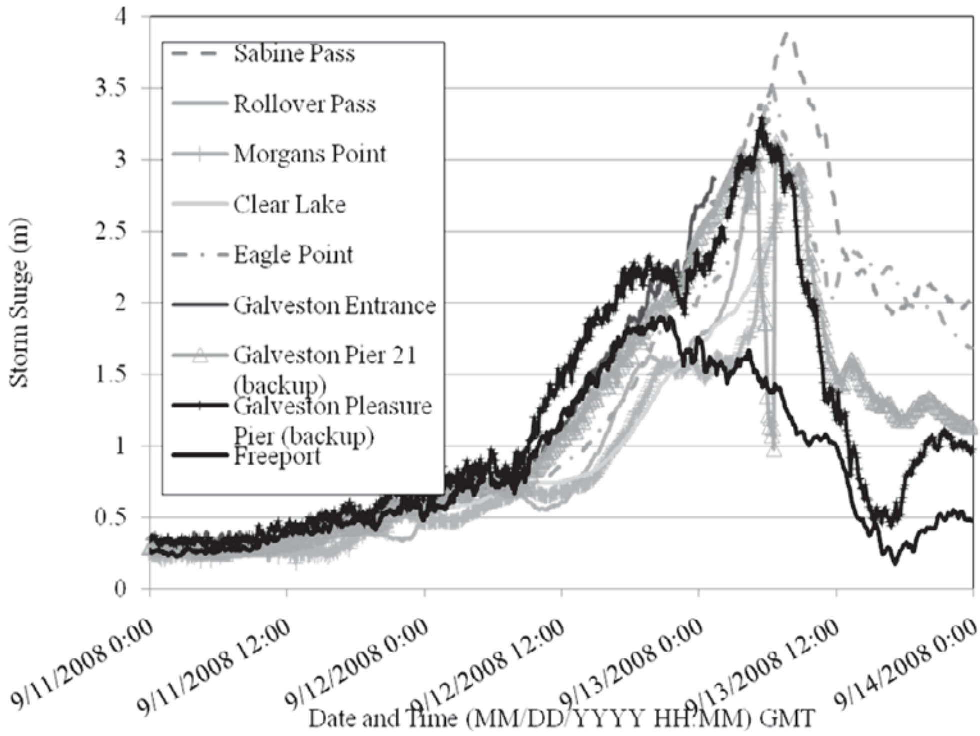


Figure 3-4. Storm surge hydrographs recorded at Galveston area NOAA stations. Each curve shows measured minus predicted water levels for a particular location; wind waves have been filtered out

Table 3-1. Measured NOAA Water Level and Wind Data for Hurricane Ike

Station Name and Number	*Latitude*	*Longitude*	*Max Meas. MWL (NAVD88, m) and time (GMT, 13 Sep 2008)*	*Peak storm surge (m; at time of max water level unless noted)*	*Max 1-minute wind speed (m/s) and time (GMT, 13 Sep 2008)*
Sabine Pass North (8770570)	29° 43.8' N	93° 52.2' W	5.39, 0800	3.90, 0748	31.5, 0548
Rollover Pass (8770971)	29° 30.9' N	94° 30.8' W	4.52, 0548 (failed at 0600)	3.37	26.2, 0400 (failed at 0400)
Morgans Point (8770613)	29° 40.9' N	94° 59.1' W	4.34, 0706 (failed at 0712)	2.69	23.7, 0612 (failed at 0712)
Clear Lake (8770933)	29° 33.8' N	95° 04' W	4.04, 0600 (failed at 0600)	2.42	14.0, 0400 (failed at 0600)
Eagle Point (8771013)	29° 28.8' N	94° 55.1' W	4.90, 0624	3.50	30.5, 0606 (failed at 2036)
Galveston Entrance, North Jetty (8771341)	29° 21.5' N	94° 43.5' W	5.75, 0112 (failed at 0124)	2.87	26.2, 0218 (failed at 0254)
Galveston Pier 21 (bay side) (8771450)	29° 18.6' N	94° 47.6' W	3.42, 0648	3.12	N/A
Galveston Pleasure Pier (8771510)	29° 17.1' N	94° 47.3' W	3.55, 0530	3.29	26.8, 0512
Freeport (8772447)	28° 56' N	95° 18' W	10.65, 2000 on 12 Sep 2008	1.91, 2042 on 12 Sep 2008	26.2, 0524

Notes: Based on preliminary data; all times are GMT.
Nominally one record every 6 minutes, except for Rollover Pass (hourly).

Offshore Wave and Surge Measurements

Prof. Andrew Kennedy of Notre Dame University deployed nine gauges, which recorded surges and waves offshore the Texas coastline from Corpus Christi to the Texas-Louisiana border in advance of Hurricane Ike. Eight of these gauges were recovered and provided good data. These gauges were deployed by helicopter in advance of the hurricane in water depths of approximately 9 m and have a recording capacity of at least nine days. Prof. Kennedy generously provided some of these data for inclusion in this report.

Storm Surges

Figure 3-5 compares the water levels from the Kennedy gauges near Galveston, Bolivar Peninsula, and Rollover Pass with tide gauges at Galveston Pier, Rollover Pass, and Sabine Pass. Note that the Galveston Pier tide gauge failed just prior to the peak storm surge; its results are presented in all three panels for comparison purposes. In all cases, the black lines represent the Kennedy gauge results. For the results presented, the peak storm surge occurs at Sabine Pass and is approximately 4.6 m above MSL.

Waves

Figure 3-6 presents measurements of significant wave heights from all eight gauges that provided data along the Texas Coast. Also included are (1) the measured wave heights from NDBC Buoy 42035 that broke mooring and drifted during the storm and (2) the significant wave heights if the waves were in local equilibrium with the winds at the time. The time axis is relative to "Landfall Day," and with the exception of the X and Z gauges, the peak waves occurred approximately one-half to three-quarters of a day prior to landfall. A somewhat similar effect occurs with the storm surge (Figure 3-5) in which an early peak occurs prior to the major peak, which has been considered a possible forerunner (Bunpapong et al. 1985).

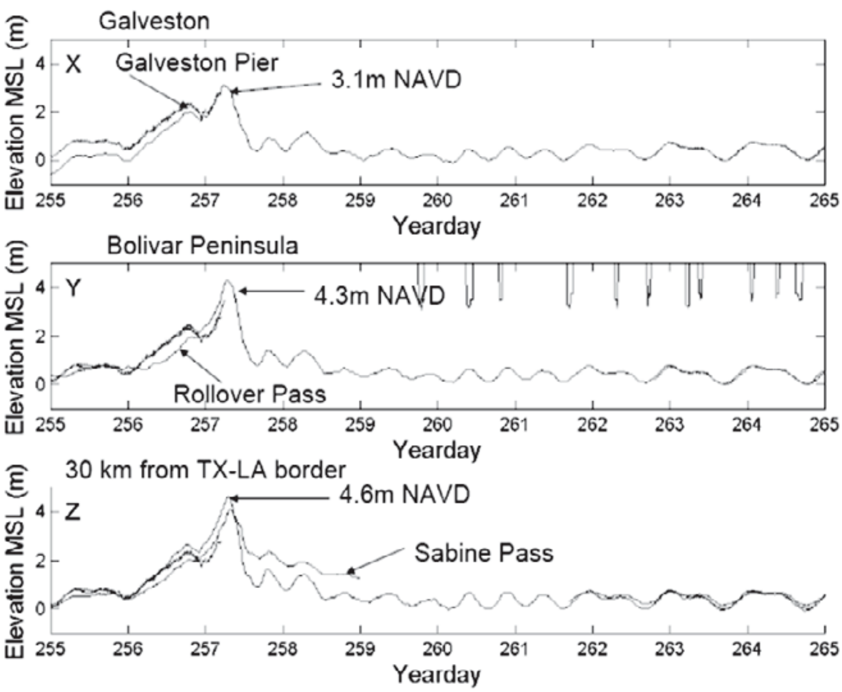


Figure 3-5. Storm surge results based on three Kennedy gauges compared to tide gauge results at Galveston Pier, Rollover Pass, and Sabine Pass. The Galveston Pier water levels are shown on all three panels for comparison purposes. Note that the Kennedy gauges recorded throughout the entire storm, despite being in approximately 9 m of water.

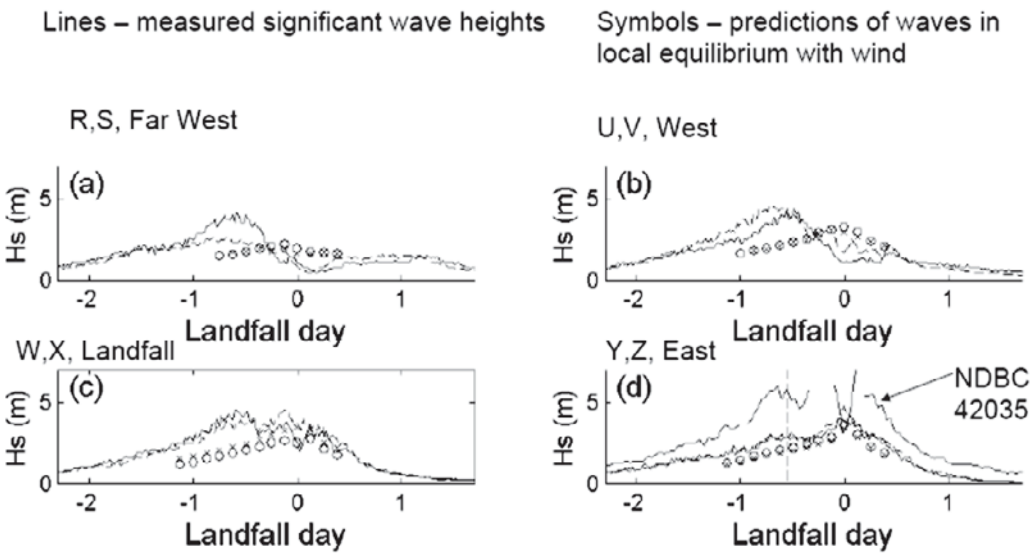


Figure 3-6. Significant wave height at all eight Kennedy gauges that recorded waves during Ike. Also shown are (1) the measured wave heights from NDBC Buoy 42035 that broke mooring and drifted during the storm and (2) the significant wave heights if the waves were in local equilibrium with the winds at the time. The time axis is relative to the day Ike made landfall.

Summary

In summary, the peak surges and significant waves measured in water depths of approximately 9 m by the eight Kennedy gauges during Hurricane Ike were approximately 4.6 and 4.0 m, respectively. Two major elements are of special interest in this storm: first, an early peak in the storm surge records and, second, the maximum waves in six of the eight gauges preceded the maximum winds by one-half to three-quarters of a day.

Meteorological Parameters

Each of the water-level measurement stations discussed also included measurements of meteorological parameters. Maximum 1-minute winds are shown in Table 3-1. Several of the anemometers failed during the storm, but it appears that most survived up to nearly peak wind speeds, and some recorded maximum 1-minute winds exceeded 30 m/s. None of the stations recorded winds above tropical storm strength, however. The maximum 1-minute measurement recorded was 31.5 m/s at Sabine Pass, where the maximum storm surge was also found.

The wind field at landfall constructed by NOAA's Hurricane Research Division (Figure 3-2) indicates maximum wind in the vicinity of High Island, near the eastern end of the Bolivar Peninsula. The NOAA coastal wind sensors that bracket this location are located at Sabine Pass and Rollover Pass. Of the NOAA stations, the anemometer at Sabine Pass yielded the greatest 1-minute reading in the storm.

The anemometer at Rollover Pass (hourly data) failed 2 hours before the peak wind at Sabine Pass was measured. The maximum 1-minute wind measured at Rollover Pass was 26.2 m/s. It seems likely that this failure resulted from storm surge and waves destroying the infrastructure that supported the anemometer. The bridge at Rollover Pass was heavily damaged with only one lane remaining.

The drop in wind speed as the eye of the storm passed, followed by a rapid increase in wind speed, is evident in the Eagle Point and Galveston Pleasure Pier data sets shown in Figure 3-7. The trend in wind gusts is similar (Figure 3-8). A simultaneous 180-degree reversal in wind direction is also evident as the storm passed over the Eagle Point gauge (Figure 3-9). Several groups deployed temporary anemometers prior to the storm, which were expected to significantly improve the observations of the wind field as the storm moved over land.

The barometric pressure time series is consistent with the trends in the wind data, as expected (Figure 3-10). The minimum recorded pressure was 951.7 mbar at Galveston Pleasure Pier.

An anemometer on resident John Russell's roof in The Biscayne development on the Bolivar Peninsula (N30 38.361 W94 04.174) worked through most of the storm. Russell recorded a maximum wind speed of 46 m/s from the northeast before his anemometer broke. The bottom clearance of his house was about 4.3 m, placing the roof at about +10 m above original ground level (Figure 3-11).

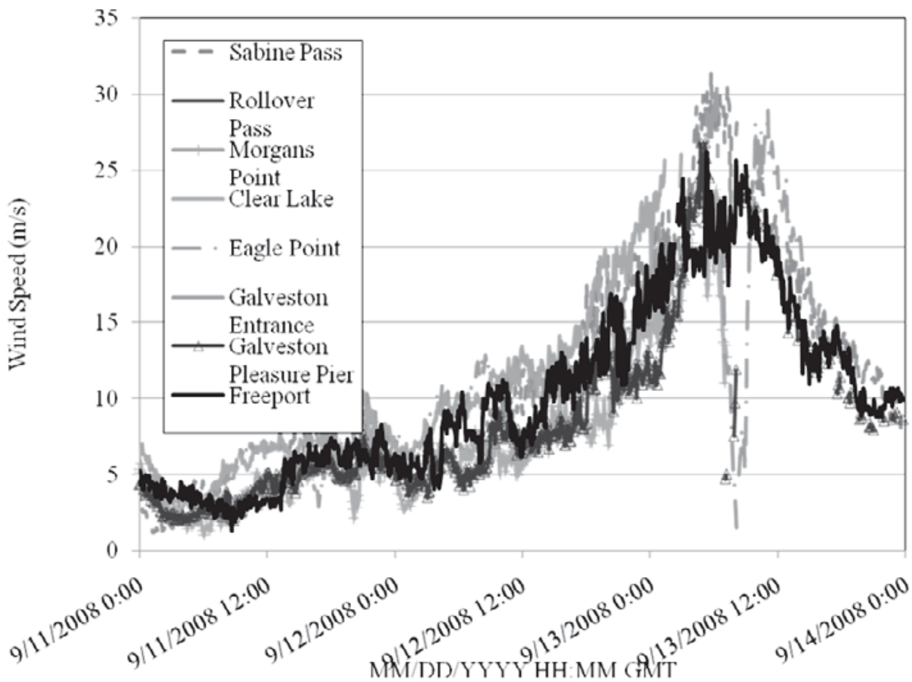


Figure 3-7. One-minute wind speeds reported at NOAA stations in Galveston area

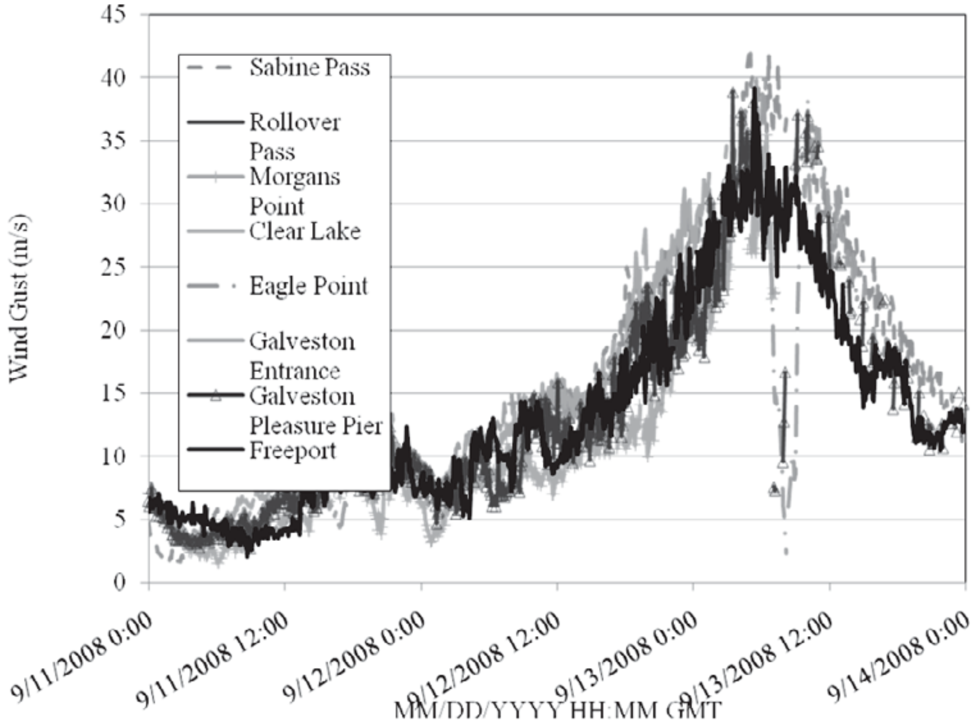


Figure 3-8. Wind gust (maximum instantaneous wind) time series recorded at NOAA stations in the Galveston area

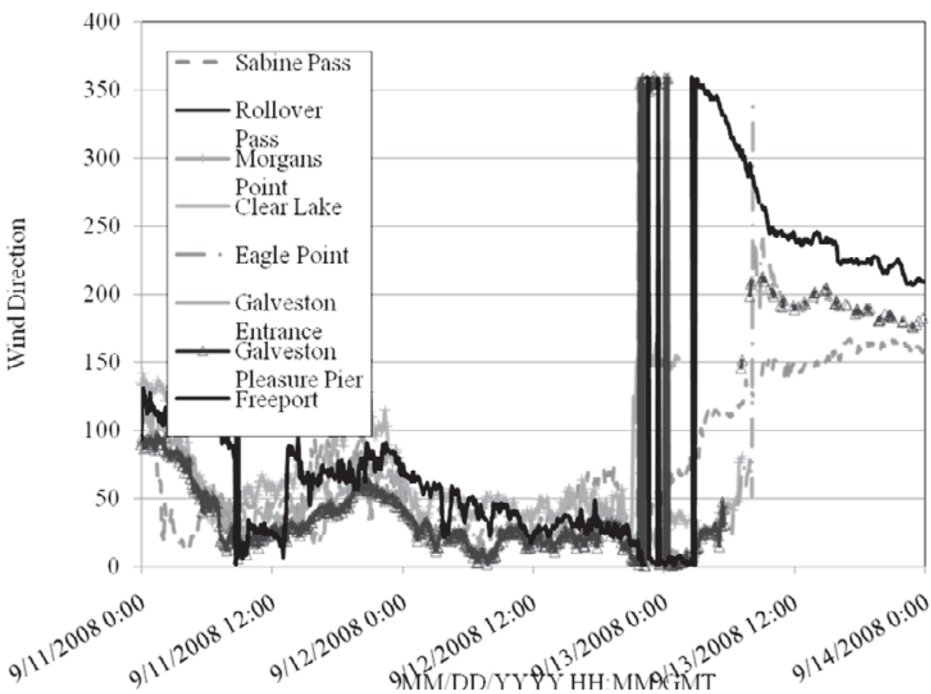


Figure 3-9. Direction of 1-minute winds at NOAA stations. Reported direction corresponds to the compass heading to the origin of the wind vector

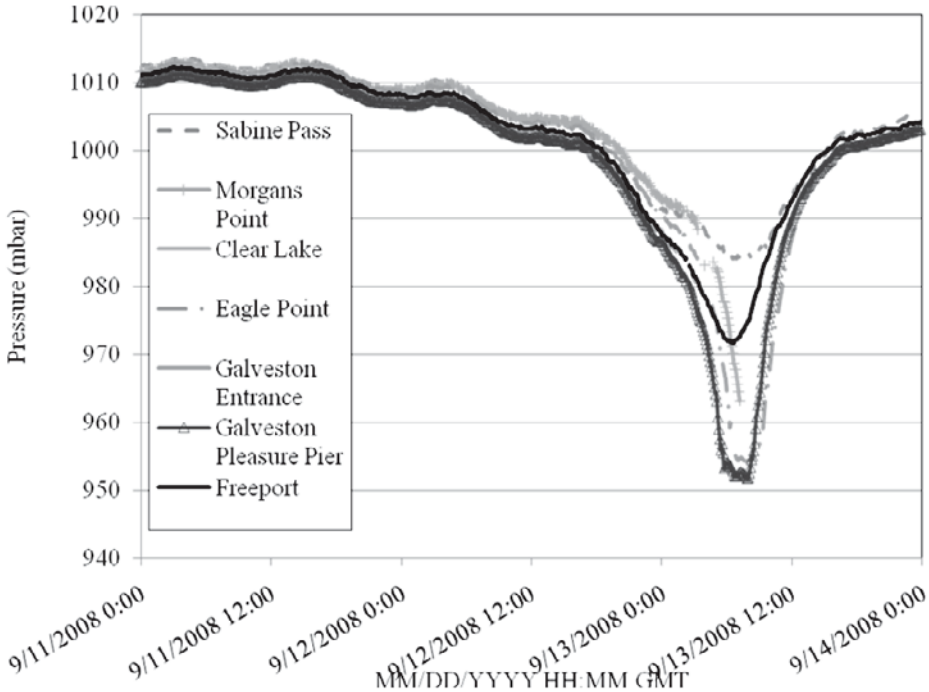


Figure 3-10. Barometric pressure at NOAA stations. Minimum recorded pressure was 951.7 mbar at Galveston Pleasure Pier

Figure 3-11. The home of John Russell on Bolivar Peninsula

Comparison With Earlier Storms

The Galveston area has received hurricane damage on many occasions. Seventeen hurricanes of magnitude 3 or 4 on the Saffir-Simpson Hurricane Scale passed within 100 statute miles of Galveston between 1851 and 2008 (Figure 3-12). No Category 5 storms are on record as having made landfall within this radius (NOAA Coastal Services Center). Ninety-seven storms of magnitude 1 or 2 have passed within 100 miles of Galveston as shown in Figure 3-13; note that some storms appear twice in this database because they changed magnitude. The most frequently referenced storms that affected the area are shown in Table 3-2. Although much of the data that will ultimately define the significance of Hurricane Ike are not yet available, it is worthwhile to compare the storm to previous events.

1900 Hurricane

The 1900 storm is legendary and widely reported as the worst natural disaster in U.S. history on the basis of loss of life, with most credible reports including an estimate near 6,000 to 8,000 deaths. This is generally attributed to lack of suitable forecasting information, warnings, and evacuation, but the storm was also very significant in magnitude. Unfortunately, the meteorological infrastructure at the time was minimal and primitive, so most accounts of the storm are anecdotal or speculative (McGee 1900).

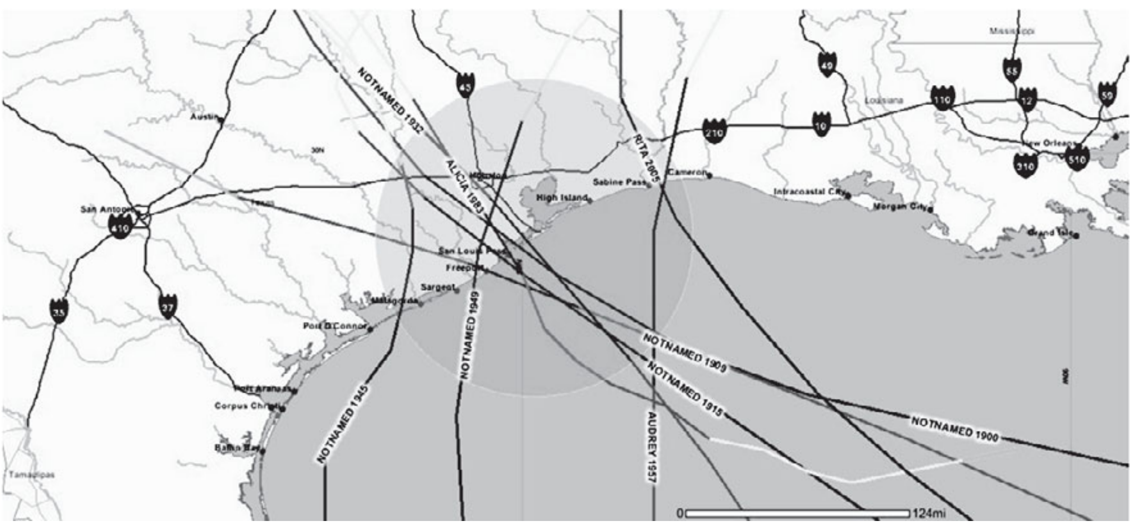


Figure 3-12. Tracks of all Category 3, 4, and 5 hurricanes passing within 100 statute miles of Galveston between 1851 and 2008. Source: NOAA Coastal Services Center

Figure 3-13. Tracks of all Category 1 and 2 hurricanes passing within 100 statute miles of Galveston between 1851 and 2008. Source: NOAA Coastal Services Center

Table 3-2. Widely Referenced Storms That Have Hit the Galveston Area

Date	Storm Name	Category (Saffir-Simpson scale)
9/8/00	Unnamed	4
6/27/57	Audrey	4
8/18/83	Alicia	3
9/24/05	Rita	3

Garriott (1900) reported that the maximum measured wind recorded at Galveston was 43 m/s (averaging period and elevation not stated) at 6:15 p.m. local time on September 8, 1900, although the observer noted that the anemometer failed as the wind increased above this value. The lowest recorded barometric pressure was 968 mbar, slightly higher than the minimum recorded pressure during Hurricane Ike.

Storm surge was clearly significant during the storm, with reports of 4.6 m cited (Hansen 2007). An effort was mounted after the storm to build a seawall and add more than 9 million m^3 of fill material behind it to protect against similar future events (Wiegel 1991). The seawall project began in 1902 and was completed in 1904. The raising of the city behind the seawall with the placement of dredge material continued until 1910. Another storm struck in 1915, but the loss of life was much less (Hansen 2007, 275).

Hurricane Audrey, 1957

Hurricane Audrey occurred early in the season and made landfall in Cameron Parish, La. The National Weather Service reports that at least 500 deaths resulted from the storm, and SLOSH model results suggest up to 4.3 m of storm surge. Maximum, 1-minute sustained winds of 33 m/s were reported in Lake Charles, La.; an unofficial report of 47 m/s was made from Sulphur, La. The minimum observed barometric pressure measured 959 mbar at Cameron, La., (Ross and

Blum 1957). High water at Galveston reached 1.9 m above MSL, with a value of 3.2 m above MSL at Cameron, La. (Ross and Blum 1957).

Hurricane Alicia, 1983

Hurricane Alicia made landfall near the western end of Galveston Island as a Category 3 hurricane, although it did not become a hurricane until it was already in the northern Gulf of Mexico and close to land. The U.S. Coast Guard Cutter Buttonwood, which was moored at Galveston, reported sustained winds of 43 m/s, and Hobby Airport in Houston reported 42 m/s sustained winds. The lowest barometric pressure measured on land associated with the storm was 967 mbar at the Alvin, Tex., National Weather Service station. The maximum storm surge reported was 3.6 m at Seabrook on Galveston Bay. Twenty-one people were reported dead because of the storm.

Hurricane Rita, 2005

Rita made landfall near the Texas-Louisiana border as a Category 3 storm, with sustained winds of 54 m/s. Storm surge of 4.5 m was reported in western Louisiana with enough storm surge near New Orleans to damage levees that had been repaired after failing in Hurricane Katrina the previous month. Hurricane Rita arrived less than a month after Hurricane Katrina had destroyed large sections of Mississippi and Louisiana via wind, storm surge, and flooding. This is the first time on record that two storms had reached Category 5 strength in the Gulf of Mexico in the same season, although neither maintained this strength at landfall. At one point, Rita had a minimum central pressure of 897 mbar. Only Hurricane Gilbert in 1988 and the Labor Day Hurricane of 1935, which struck the Florida Keys, have lower documented pressures.

Chapter 4: Geologic Conditions

Morphologic Classification

The upper Texas Coast can be divided into four geomorphic units based on the geologic framework associated with the rivers and shoreline development over geologic time (Figure 4-1).

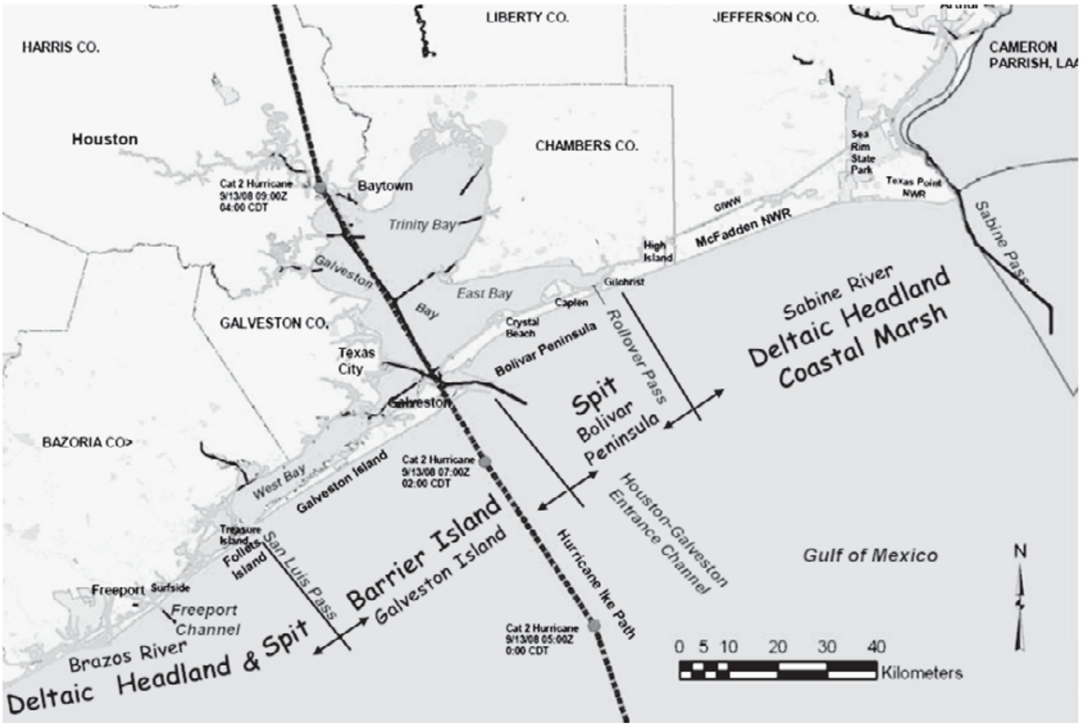


Figure 4-1. Map of the geomorphic zones along the upper Texas Coast

The four geomorphic units are (from east to west):

1. The Sabine River deltaic headland and marsh coast, which extends from the mouth of the Sabine River west to near Rollover Pass. This area is the delta of the Sabine River and is characterized by a thin veneer of sand over a fine-grained marsh and clay beds.
2. The Bolivar Peninsula is a barrier spit attached to the deltaic headland on the west. It ends at the Houston-Galveston Entrance Channel and is separated from the mainland by East Bay. This area contains more sand-size sediments with a wider sandy beach and low dunes. Rollover Pass, a man-made cut, is located near the attachment to the mainland end of the spit.
3. Galveston Island is a barrier island, separated from the mainland by West Bay and extending from the Houston-Galveston Entrance Channel to San Luis Pass. The Galveston Seawall is in front of the downtown area and has 15 stone groins perpendicular to the wall. There was a beach in front of the wall, but in recent years, fill was placed in some of the groin compartments. After Ike only pocket beaches existed there. Along the east end of East Beach adjacent to the jetty, a relatively wide beach lined with fine sand, has accreted in front of the seawall that trends toward the northwest on the eastern end of the island. West beach, which

extends from the west end of the seawall to the San Luis Pass, is composed of a sandy beach backed by a low dune.

4. From San Luis Pass to Freeport Channel the coast is composed of a barrier spit backed by Christmas Bay. This area was originally Follets Island, a barrier island that merged with the deltaic headland of the Brazos, San Bernard, and Colorado rivers. This area has some sandy material but also has a fine-grained marsh and deltaic mud under a thin veneer of sand, similar to the Sabine River headland.

The bathymetry of the nearshore shelf is transitional from a wide shallow shelf on the east to a narrower shelf on the west. Three banks are located on the approximately 75-km-wide (-20-m contour) east shelf and represent former shoreline positions. Sabine Bank, the largest, is 25 km off the Sabine River mouth in Jefferson County; Heald and Shepard banks are about 50 and 60 km, respectively, off the mouth of the Houston-Galveston Navigation Channel entrance. Off Galveston Island and westward, the shelf narrows to about 25 km based on the -20 m contour.

Aerial Photography Analysis of Impacts

Aerial photography was available from the Texas General Land Office to represent pre-storm conditions. A digital orthorectified set of photography was flown in May 2006 for the upper Texas Coast. This photography was color infrared with a 0.3 m resolution and horizontal coordinates of NAD83 UTM zone 15. The photography was placed in an ArcMap GIS for accurate positioning in a geographic framework. The 2006 shoreline was digitized from the photographs in ArcMap using the visible high-water line.

Post-storm aerials were collected by NOAA and its National Ocean Service (NOS) and National Geodetic Survey (NGS) Remote Sensing Division on September, 15 and 18, 2008 within a few days of the storm landfall. This photography was color with a 0.5 m resolution and coordinates in NAD83 UTM zone 15. The orthoretification was done quickly, with a reported accuracy within 1 to 3 m horizontal position. A "storm" shoreline was digitized using the aerial photography at the landward extent of the beach identified as the boundary between the upland (in most locations this was a scarp in the lawns of upland property) and the beach or a post-storm high water line. In almost all cases in the four geomorphic areas, the dune line was eroded and that sand was transported landward into upland properties. A landward extent of sand overwash transport was also mapped along the study area. In most cases, the storm surge went further inland than the sand overwash, but a distinct line was visible on the photographs where the sand deposition ended.

Geomorphic Change Observations

Sabine River to Rollover Pass—Deltaic Headland

From Sabine Pass westward to just before Rollover Pass, the shoreline is composed of deltaic plane and marsh deposits as shown schematically in Figure 2-2 and photographically in Figure 4-2. The shoreline and coastal evolution have been controlled by sediments deposited at the mouth of the Sabine River as the sea level rose and from transport onshore from the nearshore. The shoreline is characterized with a flat slope with little or no beach and dune development, which progresses landward into an extensive coastal marsh (Figure 4-2). This mainland coast encompasses all of the Jefferson and Chambers counties and extends just into the Galveston County shoreline. Texas Highway 87 ran along the shoreline for the entire length of Jefferson County, but erosion and landward movement of the shore has eroded the roadway. The road has been abandoned through the McFadden National Wildlife Refuge as even small storms have washed out each attempt to repair it.

Figure 4-2. Low relief of the Sabine River deltaic headland. Texas Highway 87 and extensive coastal marsh are landward of the narrow beach

Prior to the storm, the shoreline at Sea Rim State Park was a narrow thin layer of sand over the deltaic fine-grained material (Figure 4-3a). A low dune abutted the beach and opened into a coastal marsh and prairie as seen in the May 2006 pre-storm aerial photograph. Historic shoreline positions from TxBEG and NOAA show that the shoreline experienced both erosion and accretion in this area of the Sabine River delta. Both the 1957 and 1974 shorelines were landward of their present location. (See Figure 2-3 for the location of the Jefferson County close up aerial photographs.) The back-beach marsh drains onto the beach through small creeks, cutting through the low dune line that is visible in the photo. The marsh surface can be seen as an outcrop (dark layer) in the lower foreshore.

The post-storm photographs taken five days after landfall shows flattened dunes and overwash sand deposits extending up to 220 m inland around the drainage creek. Observations from the field team found evidence of a surge some 20 km inland covering most of this flat, coastal prairie. An interesting feature in this area of the bend in the deltaic shore is the outwash fans of sand that extend back into the gulf (Figure 4-3b). Presumably, these features were formed after the storm's passage because the water that piled up from the surge drained back out into the gulf. This is a form of reverse overwash, and it deposited sand into the surf zone.

Further west along the Jefferson County shoreline in the vicinity of the McFadden National Wildlife Refuge, the pre-storm beach is characterized by a narrow sandy beach with prevalent overwash deposits extending inland between 50 and 125 m (Figure 4-4a). This overwash is relict of past storms in the area and has covered the former Route 87 roadway. The historic shoreline positions show a consistent landward retreat in this area from the 1882 shoreline to present

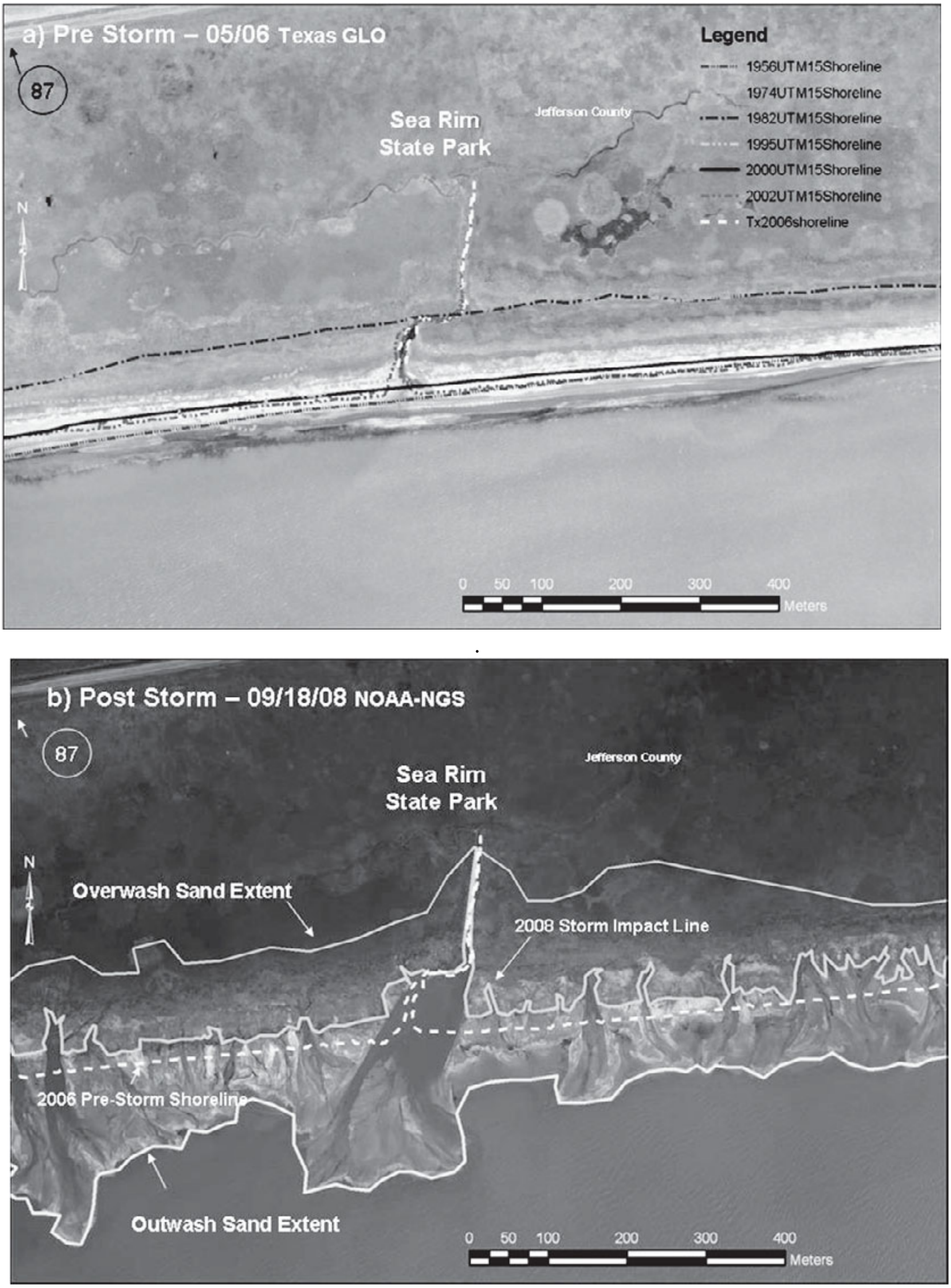


Figure 4-3. Pre-storm aerial photograph of the Sea Rim State Park area, showing (a) historic shoreline positions and (b) post-storm beach response with outwash of sand into the gulf

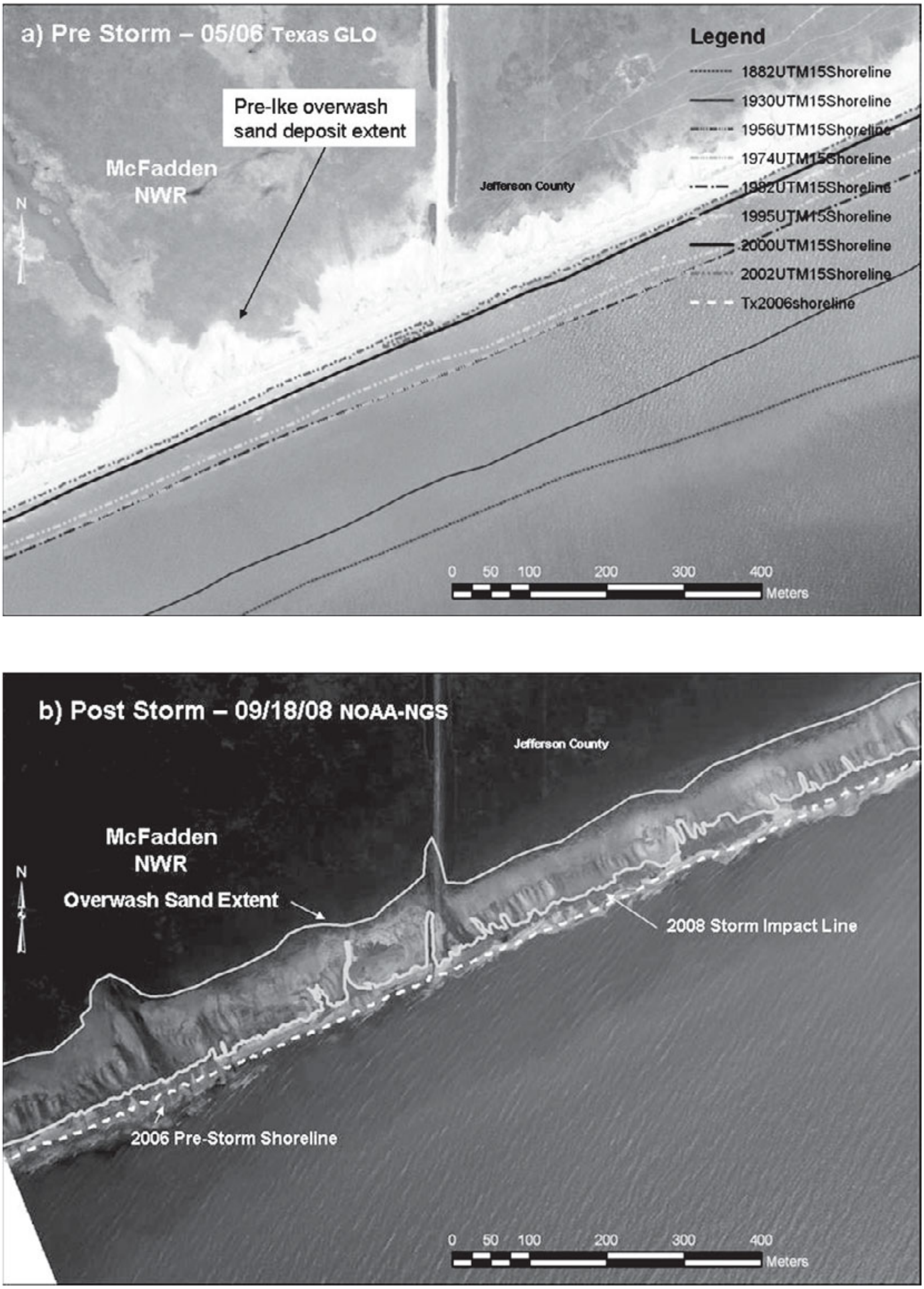


Figure 4-4. (a) Pre-storm aerial photograph of the McFadden NWR area showing historic shoreline positions and pre-Ike overwash and (b) post-storm overwash extent and shoreline position

Five days after landfall, the coast shows extended overwash into the marsh. The extent of the sand transport as overwash was more extensive than relict overwash fans from previous storms, extending between 100 and 150 m into the marsh from the 2006 pre-storm shoreline (Figure 4-4b). The surge transported water much further inland, but with limited sand in the natural system, the overwash fans were limited to a maximum penetration distance of 150 m. An abandoned side road visible in the center of the photograph allowed sand to be transported further inland. Several drainage channels are visible across the beach, possibly formed by the surge water returning to the gulf after the storm. All the low dunes were removed by the storm in this area.

Bolivar Peninsula—Barrier Spit

Bolivar Peninsula is part of the barrier spit, which is separated from the mainland by East Bay (Figure 4-5). The town of High Island sits around a salt dome at the eastern end of the mainland part of Galveston County; the town of Gilchrist is several miles farther west. Rollover Pass, a manmade cut through a narrow section of the spit, was created to allow for improved circulation and flushing of East Bay. Rollover Pass has been stabilized by a sheet pile wall on both sides of the pass with wider U-shaped flanking walls on both the east and west sides on the gulf.

The spit (technically now a barrier island) has two wide areas, possibly old inlet sites that are now part of the peninsula. The town of Caplen is west of Rollover Pass at the first wide area. Crystal Beach is located about mid-peninsula at the second wide area. The eastern end of the peninsula has a series of recurved beach ridges, indicating that the spit is growing to the west.

The area east of Rollover Pass is the town of Gilchrist, which is composed of single-family homes. The pre-storm photographs show a relatively densely populated area with a 25-m-wide sandy beach. Because the spit grew to the west over time, this area remained a narrow 400 m wide strip (Figure 4-6a). The historic shorelines show a progressive erosion pattern since 1957. Sand-filled geotextile tubes have been installed, and a dune was built over them to protect the beachfront on both sides of the pass.

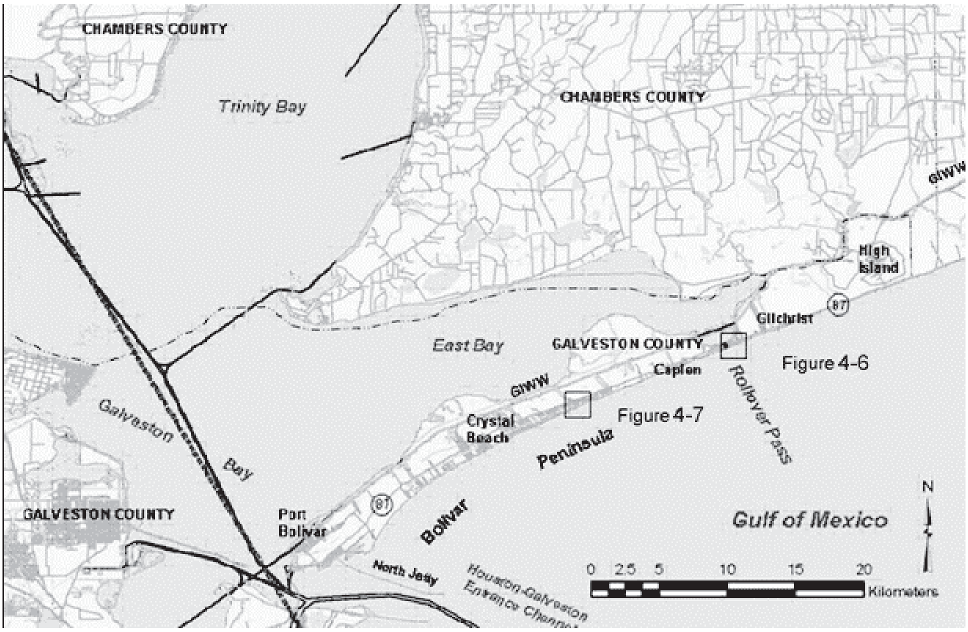


Figure 4-5. Location map of Bolivar Peninsula, a barrier spit. Boxes show location of Figure 4-6 and Figure 4-7.

Photos taken three days after landfall of Hurricane Ike showed severe erosion of the beach and near total destruction of upland structures in the Rollover Pass area of Gilchrist. The post-storm photo shows that sand had overwashed the entire narrow width of this part of Bolivar Peninsula (Figure 4-6b). Despite the geotextile protection, the beachfront experienced major erosion with the formation of localized erosion channels. Because the beach sands are a veneer over marsh deposits, the storm gouged the island where erosion channels have cut back almost to Texas 87 in many places through the softer marsh deposits. The geotextiles appeared to somewhat reduce, but not prevent, the extent of erosion farther landward compared to unprotected sections and areas where the tubes were damaged. This part of the spit was completely under water during the height of the storm, allowing the sediment to transport into East Bay. The sands remaining on the beach were composed of coarse shell hash material.

Figure 4-6. (a) Pre-storm aerial photography of Rollover Pass and Gilchrist with historic shorelines and location of buried geotextile tubes and (b) post-storm impacts of overwash extent and shoreline change

Further to the west on Bolivar Peninsula the pre-storm beach was about 25 m wide and had low dunes. Historic shoreline positions show that the beach was eroding around Crystal Beach (Figure 4-7a). A shallow canal that paralleled the beach was present behind the first row of homes in this area on the east side of Crystal Beach.

The post-storm photography, taken three days after landfall, shows that the overwash sand deposits extended more than 400 m behind the pre-storm dune line. The post-storm shoreline had moved landward of the first row of homes and had pushed sand into the canals (Figure 4-7b). Almost all of the beachfront homes were destroyed as the dune and beach eroded mostly landward as overwash. Scour holes are now located in front of most of the foundations. Marsh deposits were found on the beach where the dune line once existed. This is typical of the Crystal Beach area where the sand overwash deposit extended the furthest inland of the study area.

Galveston Island—A Barrier Island

Galveston Island is a true barrier island, detached from the mainland by West Bay. It is bordered on the east by the Houston-Galveston Navigation Channel entrance and on the west by San Luis Pass as shown previously in Figure 2-1. The island is shaped like a drumstick with its widest parts on the eastern end where downtown Galveston is located. The Galveston Seawall is located along the beachfront in this area. West Beach is located west of the seawall. Beach sand has been accumulating on the eastern end of East Beach in front of the seawall as sand is trapped by the Houston-Galveston Entrance Channel's south jetty in an area of inlet induced drift reversal. Sand is also accumulating at the west end of the island at San Luis Pass as a series of recurved beach ridges expanding toward the pass over time. The storm track shows that Ike's eye passed over the East Beach area as the storm tracked up the Houston Ship Channel toward Houston.

The eastern end of Galveston Island contains the East Beach, a 5,000-m-long accreting sandy beach in front of the Galveston Seawall extending from the south jetty of the Houston-Galveston Entrance Channel to 8th Street. The seawall merges with the East Beach at 8th Street and extends some 15 km to the west. Prior to the storm, the beach in front of the seawall was nourished and pocket beaches formed between most of the 15 rock groins. The shorelines from 1995 (Figure 4-8) show the effects of nourishment, with a narrow sand beach fronting the seawall.

West of the seawall, the beaches of West Beach are narrow (30- to 50-m-wide) with low dunes. An example of the West Beach is shown in Figure 4-9a at Pirates Beach. The shorelines show a steady landward movement since 1930. A sand-filled geotextile tube was constructed at this location and was buried below a dune feature, which is about 20 m in front of the first row of homes. Figure 4-9b shows the post-storm conditions. Overwash sand penetration occurred between 100 and 150 m landward of the 2006 shoreline. The dune was completely eroded, and the geotextile tubes were exposed. The landward extent of the post-storm beach is marked with a line.

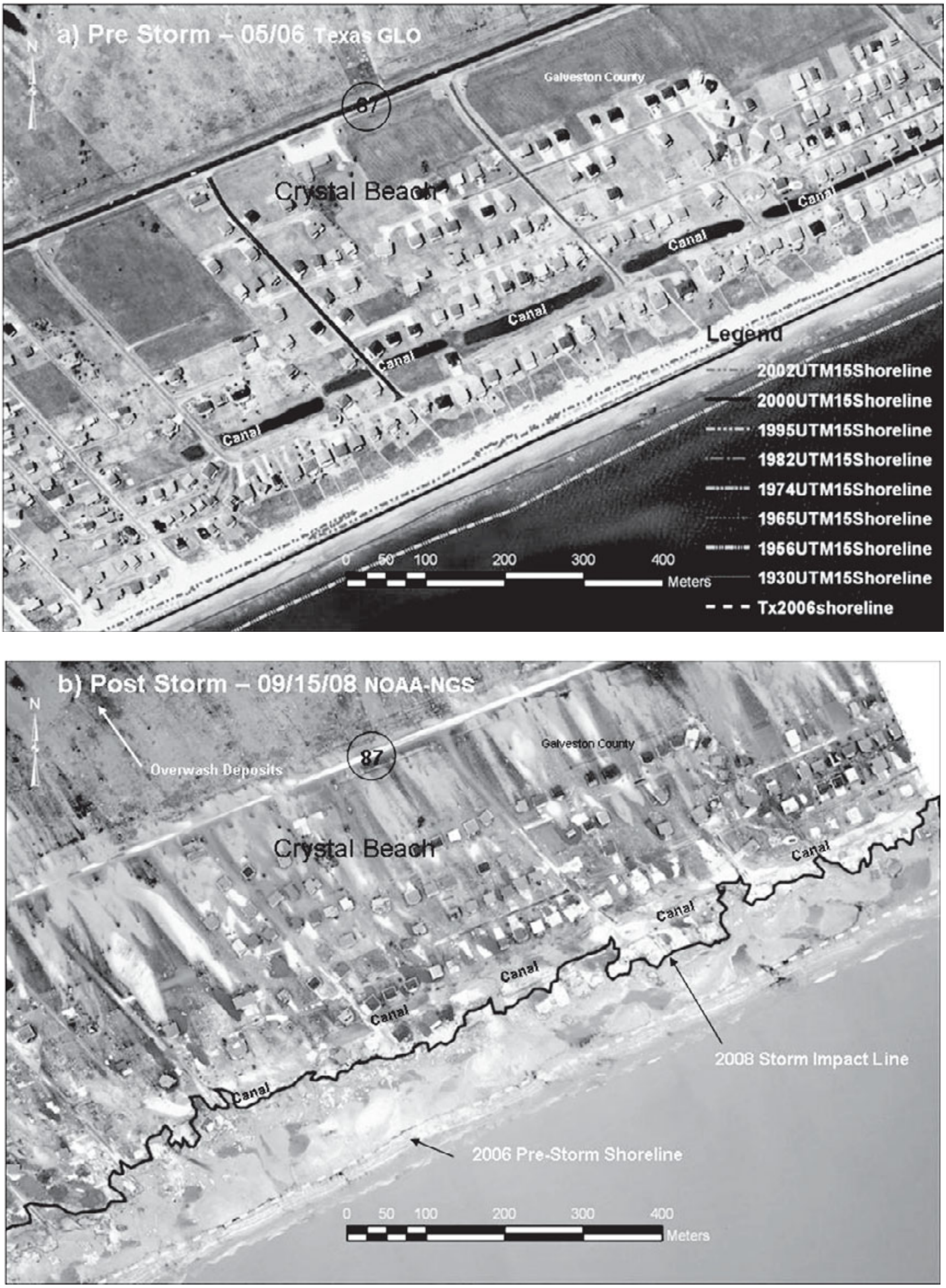
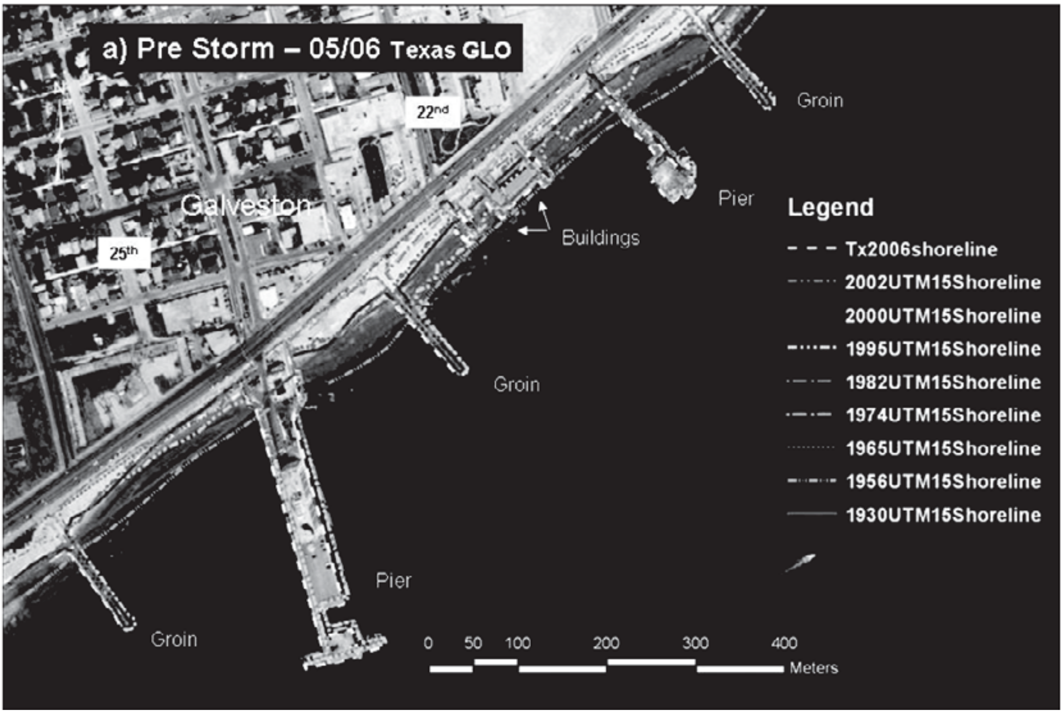


Figure 4-7. (a) Pre-storm aerial photography of Crystal Beach area, showing historic shoreline positions and canal positions and (b) post-storm impacts of overwash extending beyond boundary of photo and shoreline movement landward with infilling of canals



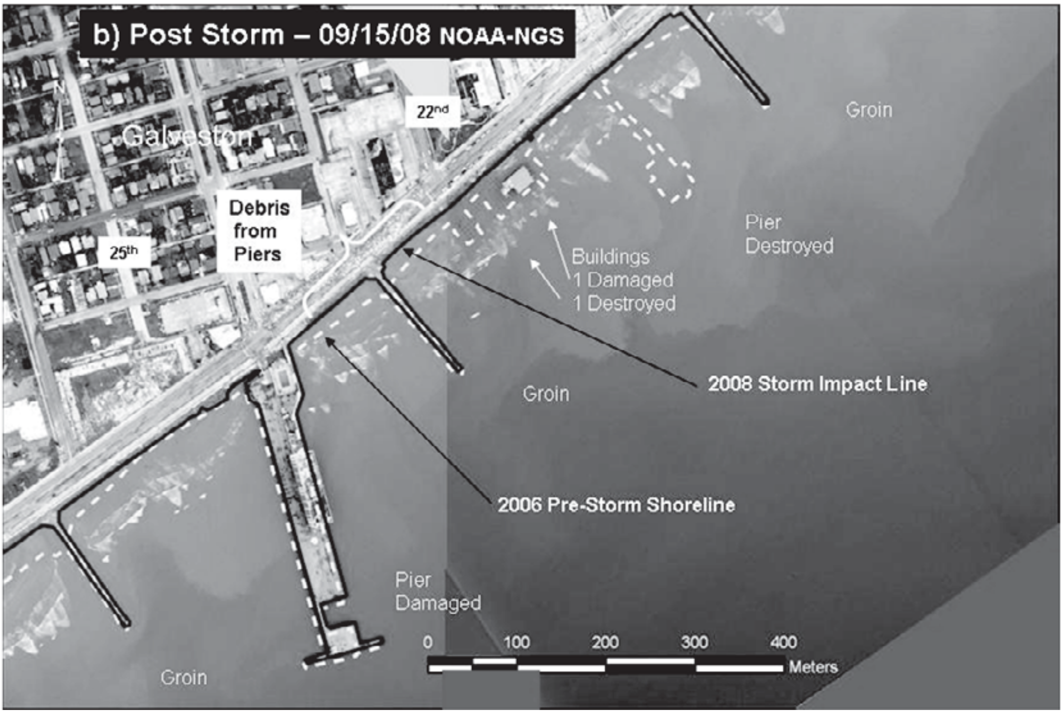


Figure 4-8. (a) Pre-storm aerial photography of the Galveston Seawall area between 21st and 26th streets showing location of piers, groins, and historic shorelines and (b) post-storm impacts of damaged and destroyed piers

Figure 4-9. (a) Pre-storm aerial photography of the Pirates Beach area of West Beach showing the historic shorelines and dune over geotextile shore protection and (b) post-storm impacts to geotextile tubes, overwash extent, and shoreline position

San Luis Pass to Freeport Harbor Entrance

The area west of San Luis Pass is a spit attached to the deltaic headland of the Brazos/San Bernard/Colorado River delta (Figure 4-10). From historic records, the 1852 shoreline showed a small island just south of San Luis Pass separated from Follets Island by a narrow pass just to the west of the present Treasure Island community. Follets Island was a barrier island separated from the deltaic headland by a narrow pass just to the east of present day Surfside. Between 1852 and 1930, both passes closed creating a spit attached on the west end to the headland and separated from the mainland by Christmas Bay. From Freeport west, the deltaic headland was formed by the three rivers depositing sediments into the gulf. Freeport Channel was the main outlet for the Brazos River until 1929 when the Brazos River Diversion Channel was constructed to redirect Brazos River sediment away from the commercial port at Freeport. The Freeport entrance delta eroded after 1929, and a new delta formed southwest of the Brazos River Diversion Channel.

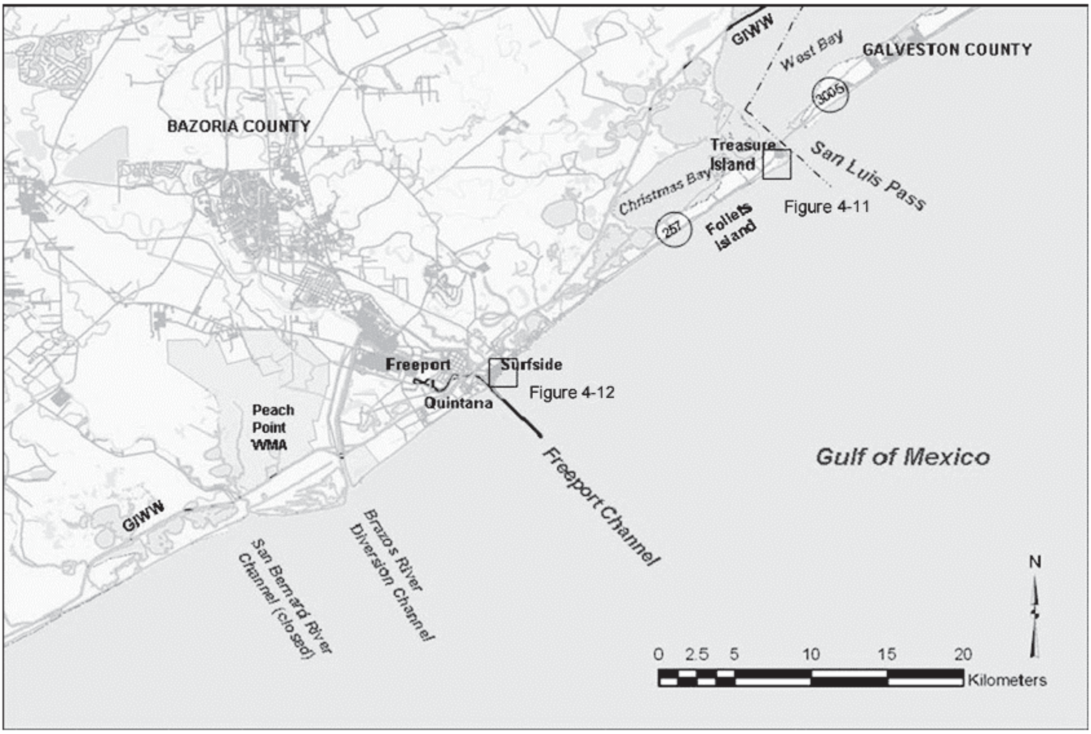


Figure 4-10. Location of the spit and Brazos River deltaic headland. Boxes show location of Figures 4-11 and 4-12

Before the storm, the west adjacent shoreline of San Luis Pass was protected by a seawall of rock and vertical concrete to shield the houses in Treasure Island. This inlet adjacent shoreline has been highly changeable as the inlet channels migrated to the west and back to the east over time (Gibeaut et al. 2003). Historic shorelines in Figure 4-11a show that the shoreline adjacent to the inlet has eroded landward some 300 m since the 1930s, requiring hard structures to protect the infrastructure landward of the shoreline when first constructed. Undeveloped land west of Treasure Island had low dunes and wide back barrier vegetated areas. Post-storm the surge overtopped the seawalls and damaged upland structures, displaced some of the seawall rocks, and destroyed a pier with a house on it (Figure 4-11b). Five scour channels were cut perpendicular across the beachface with standing water where the low dune was originally located. The storm shoreline was moved back into the vegetation some 50 to 100 m.

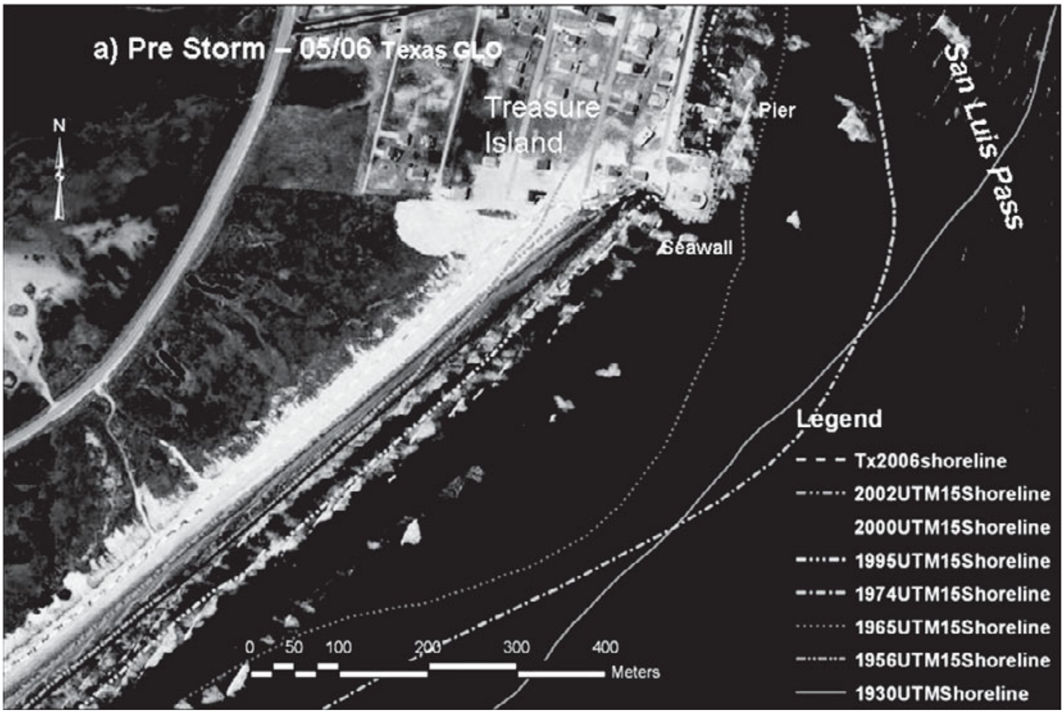
The pre-storm beach photograph at Surfside shows that the first row of houses had been on the intertidal beach since 2006. The historic shorelines at Surfside show an accretional trend in shoreline change from 1930 to 1982. Between 1982 and 1995, the Freeport Channel was widened and the east jetty was moved eastward and lengthened to its present position. From 1995 to 2002 the shoreline was fairly stable, but then moved landward some 20 m between 2002 and 2006 (Figure 4-12a). A vertical sheet pile wall was installed to protect five homes in Surfside at about the same time that the jetty was moved. A rock revetment was constructed landward of the first row of homes along the gulfward edge of Beach Drive and covered with sand. After the hurricane, the storm surge and waves eroded the dune and overwashed the road transporting sand landward some 100 m back into the community. The sheet pile wall was destroyed, and the first row of homes was destroyed or heavily damaged. The 2008 post-storm shoreline followed the rock revetment until its end and then moved landward some 75 m past the dune line and 2006 shoreline (Figure 4-12b).

Erosion Rates

In order to understand the storm-induced erosion along the upper Texas Coast, it is important to put the historic shoreline change trends into context. The TxBEG study covers changes in historic shorelines from 1883 to 2002. The study shows areas of erosion have existed along the Jefferson County shoreline, along the Texas Point NWR beach to the Sea Rim State Park beach on the east, and along McFadden NWR Beach to the west. Along Bolivar Peninsula in Galveston County, the area adjacent to Rollover Pass has also measured long-term erosion. Almost the entire length of Galveston Island has experienced long-term erosion except for accretion adjacent to the jetties. The town of Treasure Island on the southwest side of San Luis Pass has also experienced erosion (Gibeaut et al. 2002).

Using different historic shorelines, the USGS measured a short-term erosion rate (Morton et al. 2004) along the same stretch of coast. Texas Point NWR beach has experienced high erosion rates, but Sea Rim State Park has experienced some accretion in recent years. McFadden NWR beach still shows erosion in this study. The more recent erosion along Bolivar Peninsula has slowed immediately adjacent to Rollover Pass along the beachfront of the towns of Gilchist and Caplen. Accretion was measured in both the long- and short-term studies at the west end of Bolivar Peninsula indicating the spit has grown due to net drift to the southwest along the coast at the east side of the east jetty.

The USGS limited its study of Galveston Island erosion to the area west of the Galveston Seawall and to East Beach at the west jetty. This study shows erosion immediately west of the wall, then an area of little change, and finally accretion at San Luis Pass. Again the net drift along this area is to the southwest. A localized net drift reversal to the northeast is found around the south jetty of the Houston-Galveston Entrance Channel where accretion has been measured adjacent to the south jetty in both studies. Recurved spits are also present at the west end of Galveston Island adjacent to San Luis Pass. Historic accretion at this pass was measured in both studies.



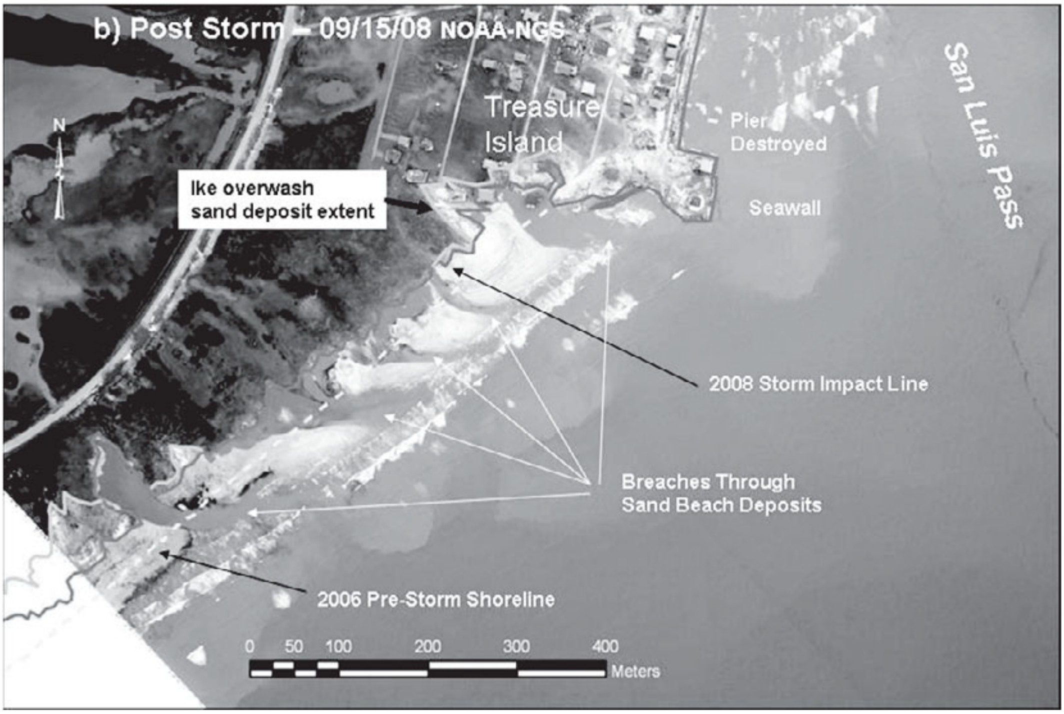


Figure 4-11. Pre-storm aerial photography of Treasure Island at San Luis Pass (a) showing historic shorelines and seawall and (b) post-storm impacts of overwash, breaches in beach, and damage to structures

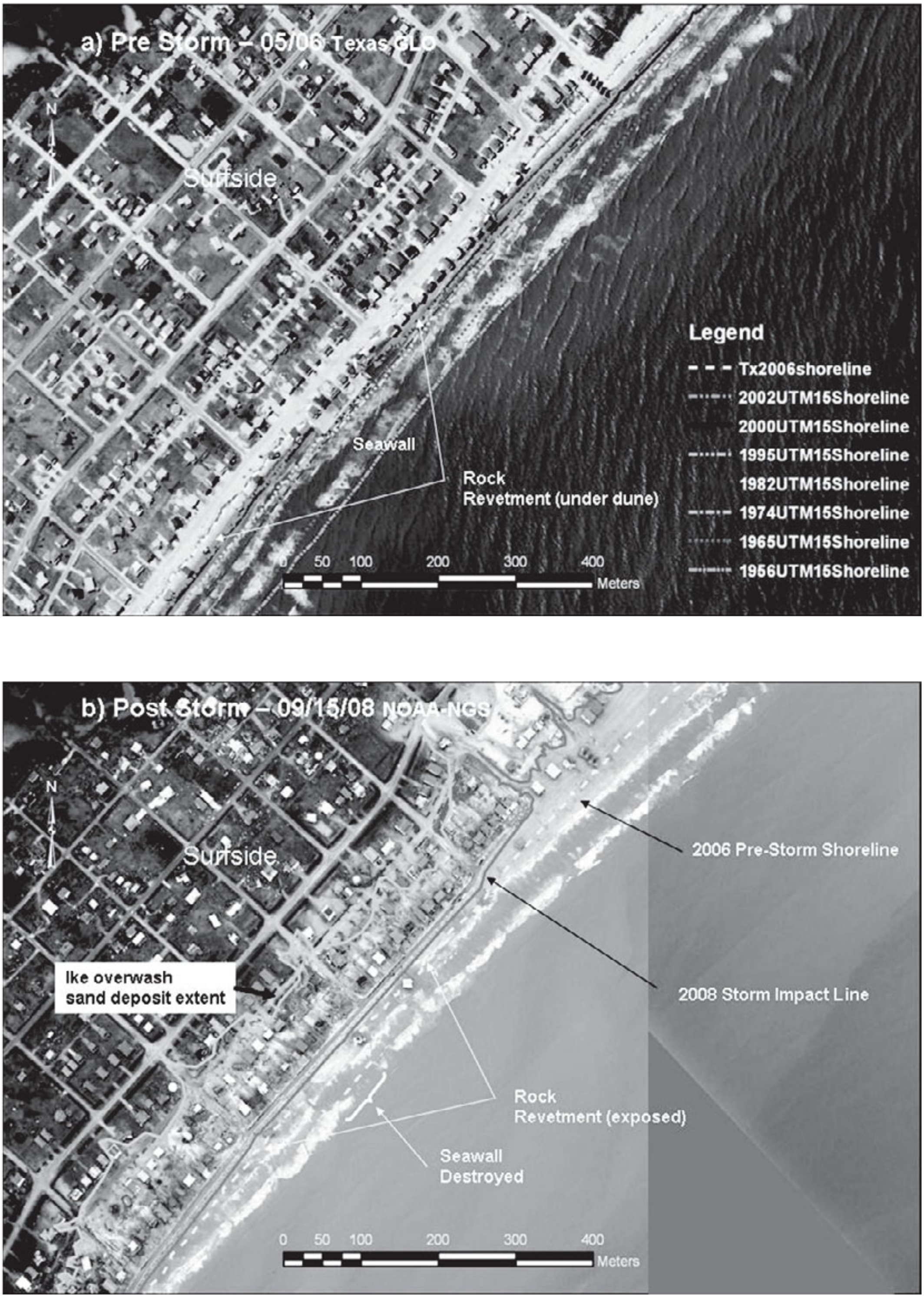


Figure 4-12. Pre-storm aerial photography of Surfside near Freeport showing (a) historic shoreline positions and (b) post-storm impacts of overwash and structural damage

The west side of San Luis Pass shows another erosion hot spot where the shoreline change was largely due to the changes in the channels and adjacent shoreline. Treasure Island has experienced erosion resulting in the construction of a seawall. The long-term BEG study shows erosion along Follets Island, but the shorter-term USGS study shows little recent change or slight accretion along this section of coast. Long-term erosion affected the Brazos River Delta just to the south of the Freeport Channel after construction of the Brazos River Diversion Channel in 1929. Long-term accretion has occurred in the vicinity of the San Bernard River Channel, which closed in about 2000. The relocation of the delta west of the new channel provided an outlet for sediment to the coast west of the new channel.

These historic shoreline change studies indicate where the chronic hot spots (areas of higher erosion than surrounding trends) exist. The impacts of Hurricane Ike were felt all along the coast but were more severe in the hot spots. Causes for this erosion include the lack of sand in the system, downdrift impacts due to shoreline protection structures, and shoreline orientation changes. See Stauble and Gravens (2004) for more details on causes of erosion hot spots.

Shoreline Position Change

To evaluate the shoreline changes from Hurricane Ike, the shoreline was digitized from the 2006 pre-storm aerial photos using GIS. The shoreline was identified as the debris line of the last high tide visible in the photographs. The pre-storm shoreline was in a similar area of the beach face as the 2002 shoreline digitized by TxBEG. This line is noted on the pre-storm aerials in Figures 4-3 through 4-12. The post-storm shoreline representation was digitized using GIS from the 2008 post-storm aerial photography. In these figures, the shoreline is shown at the landward extent of the open beach after the storm and is identified by the line between the flat beachfront and an irregular line of lawns and other vegetation edge. This line is highly irregular because of the differential erosion of the underlying clay beds common to this coast and represents the best position of the landward end of the relatively flat sandy open beach after the storm. This storm-impact line was inland of the pre-storm dune line and, in many cases, inland of the first or second row of homes, which were heavily damaged or destroyed by the wave and storm surge. Beach recovery was observed on site visits three weeks after storm landfall as a ridge and runnel feature was seen along almost the entire study area. The post-storm shoreline is returning to a more linear feature as sand is transported back to the beach by fair-weather waves.

Geologic Framework of Storm Beach Erosion

The underlying geologic framework of marsh and deltaic clays played an important role in the response of the shoreline to the storm. The response was different in each of the four geomorphic zones along the coast. The lack of sand and abundance of fine material near or at the surface in the Sabine River deltaic headland in Jefferson County caused an irregular shoreline after the storm. Many outflow channels were present across the narrow, fine-sand beach, likely formed when the large marsh area behind the beach drained back into the gulf after the storm. The deltaic headland and upper spit of Bolivar Peninsula shoreline showed a two to four layer stratigraphic surface sequence, with a basal clay unit, a thin sand relict overwash deposit, an upper marsh deposit, and a top thin sandy beach layer (Figure 4-13). This resulted in differential erosion of the beach face and dune area with resulting scour channels perpendicular to the beach where more erodable substrate was scoured by the storm surge.

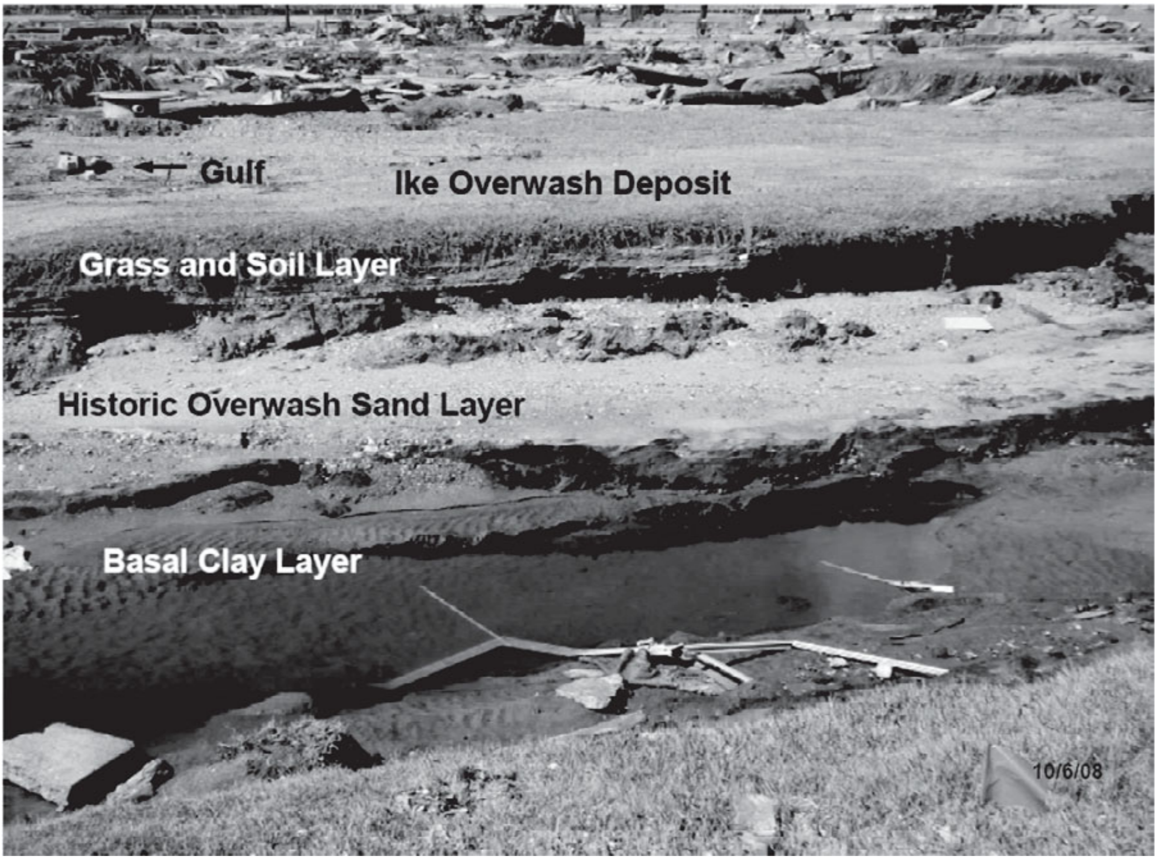


Figure 4-13. Stratigraphic layering of beach at Rollover Pass, showing four layers

As the sand content of the beachface increased, the shoreline eroded more uniformly as seen on the western end of Bolivar Peninsula and Galveston Island. In some areas, a remnant dune core of fine material was left in place in the middle of the now enlarged beach, as seen along the Bolivar Peninsula near Crystal Beach. West of San Luis Pass on the Brazos, San Bernard, and Colorado rivers deltaic headlands between Treasure Island and Surfside, the beach also exhibited irregular erosion and scour channels indicative of increased silt and clay.

Beach Recovery—Ridge and Runnel Observations

Three weeks after the storm made landfall (October 4-6, 2008), beach sand recovery was observed along the study area. This recovery was in the form of a low beach ridge located in the low-tide terrace and visible at low tide. In most places the ridge was accompanied by a runnel (or low trough) between the ridge and the high-water line on the beach foreshore. Due to the fine-grained nature of the beaches, the foreshore slope was flat, and the ridge feature had low relief. A relatively coarse and thick beach ridge composed of shell hash was found on Bolivar Peninsula just west of High Island. This ridge was not present on the September 15, 2008 post-storm aerials but was observed three weeks later. A runnel with standing water appeared landward of the linear ridge (Figure 4-14a). The entire beachface was narrow in this area. Further to the west at Crystal Beach, a low ridge had formed on the wide foreshore with a shallow runnel near or just landward of the former dune line (Figure 4-14b). This ridge was bisected by outflow channels that returned some of the water back out to the gulf. Along Galveston Island at East Beach, the ridge was very low due to the fine-grained sands present on this flat sloping beach, and there was little standing water in the shallow runnel at low tide. Figure 4-14c shows a damaged dune crossover structure (white pilings) in the background where the former low dune was located. Along the West Beach of Galveston Island a low ridge and shallow runnel was formed from accretion of new sand onto the beach (Figure 4-14d). A ridge and runnel was also observed just to the west of Treasure Island in Brazos County. The low ridge was moving up the foreshore and had a relatively deep runnel with standing water on October 6, 2008 (Figure 4-14e). This ridge was found along most of the sand spit, but no ridge and runnel were present at Surfside just east of Freeport Harbor jetty. Here the beach is narrow and fronted by a rock revetment, and no accretion via ridge and runnel was observed (Figure 4-14f).

Overwash Sand Deposit Extent

The visible limit of inland sand transport was mapped from the post-storm aerial photography to determine the linear extent and transport distance. The surge went further inland, but the sand overwash deposits provide a good picture of the transport of sand-size sediment inland. The overwash deposits were not uniform and varied within each geomorphic zone. This variation was a result of the quantity of sand available to be transported inland, pre-storm dune development, surge force, and track of the storm. The linear extent and distance inland along the Sabine River deltaic headland was limited to 150 to 200 m inland but was consistent along the zone (Figures 4-3 and 4-4). The limited available sand probably minimized the inland distance of sand transport while the surge was substantial.

Bolivar Peninsula exhibited the most landward extent of overwash sand deposits, which was located near Crystal Beach. Substantial landward penetration of the sand was seen all along this spit. Bolivar Peninsula and the Sabine River deltaic headland were on the right front quadrant of the storm and, thus, received the most intense winds, waves, and surge from Ike. They also received the largest overwash extent of sand in the study area. Figure 4-15a shows the landward extent of the overwash fan deposits over the marsh and back beach surface around Gilchrist. The depth of the deposit was roughly estimated at 0.3 to 0.6 m at Crystal Beach (Figure 4-15b). Sand transport filled beach parallel canals at Crystal Beach (Figure 4-15c). The sand was transported about 0.5 km inland at the narrow Gilchrist area and from 1 to 2 km inland at Crystal Beach.

The landward extent of the overwash sand deposits is greatest along the Bolivar Peninsula, with the maximum landward extent of sand transport observed located just west of Crystal Beach (Figure 4-16a). This area was on the right front quadrant of the hurricane and took the full brunt of the storm surge, waves, and onshore winds.

Overwash sand transport on Galveston Island raged between 100 and 200 m inland along West Beach. The Galveston Seawall and lack of sand on the beach prevented overwash along Seawall Boulevard. Galveston Island, except for East Beach, was in the less intense left front quadrant of the storm. This may have limited the landward extent of overwash transport because the winds were in the opposite direction to the waves and surge. The accreted eastern end of East Beach, which was gulfward of the seawall, had about 100 m sand transported inland by overwash. The largest landward extent of sand transport on the island was just west of the Galveston Seawall. Overwash sand was transported inland over the beach highway along much of West Beach, except for the western end near San Luis Pass. Figure 4-15d shows the thin deposit of sand on the landward side of the highway approximately 200 m into the island near Jamaica Beach. Mapping the extent of sand overwash along Galveston Island shows that the maximum overwash occurred just to the west of the seawall (Figure 4-16b). Water was pushed further inland over the island, but the sandy sediment was limited due to the thin sand deposits overlying clay deposits.

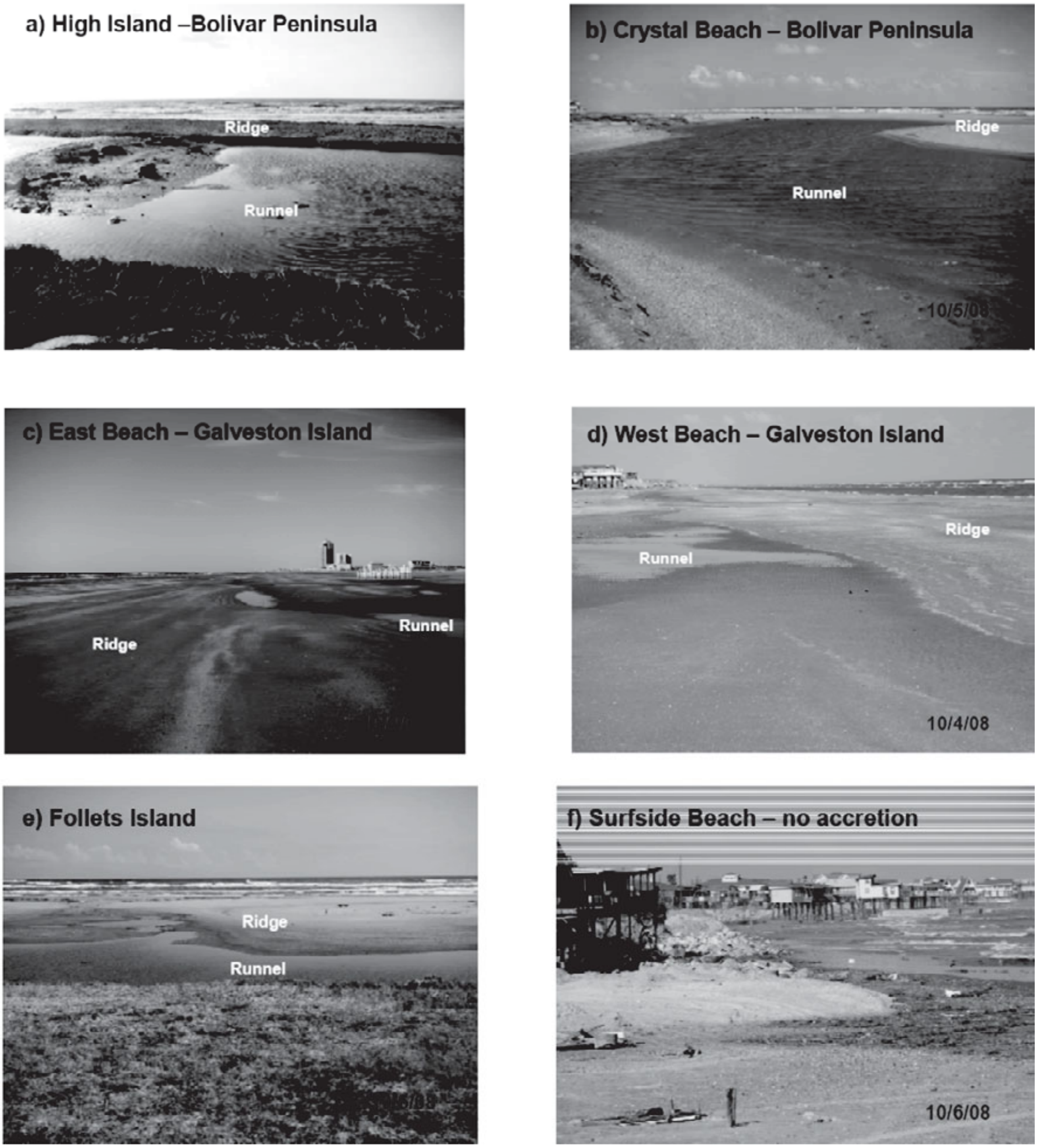


Figure 4-14. Ridge and runnel accretionary features observer in the study area, (a) in vicinity of High Island—coarse shell hash ridge, (b) Crystal Beach area of Bolivar Peninsula, (c) East Beach of Galveston Island, (d) West Beach of Galveston Island, e) west of Treasure Island in Brazoria County, and (f) no ridge and runnel present at Surfside

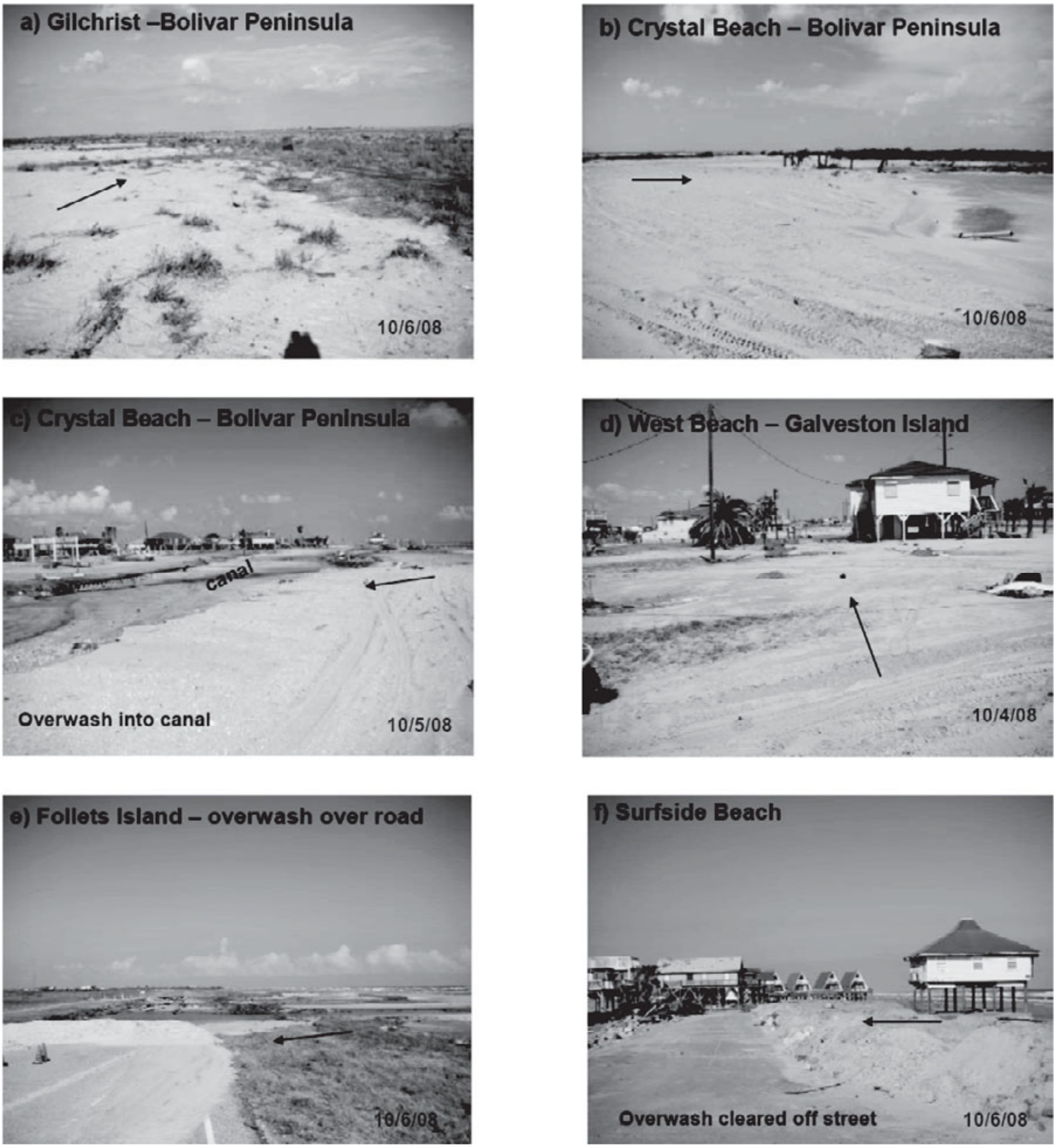
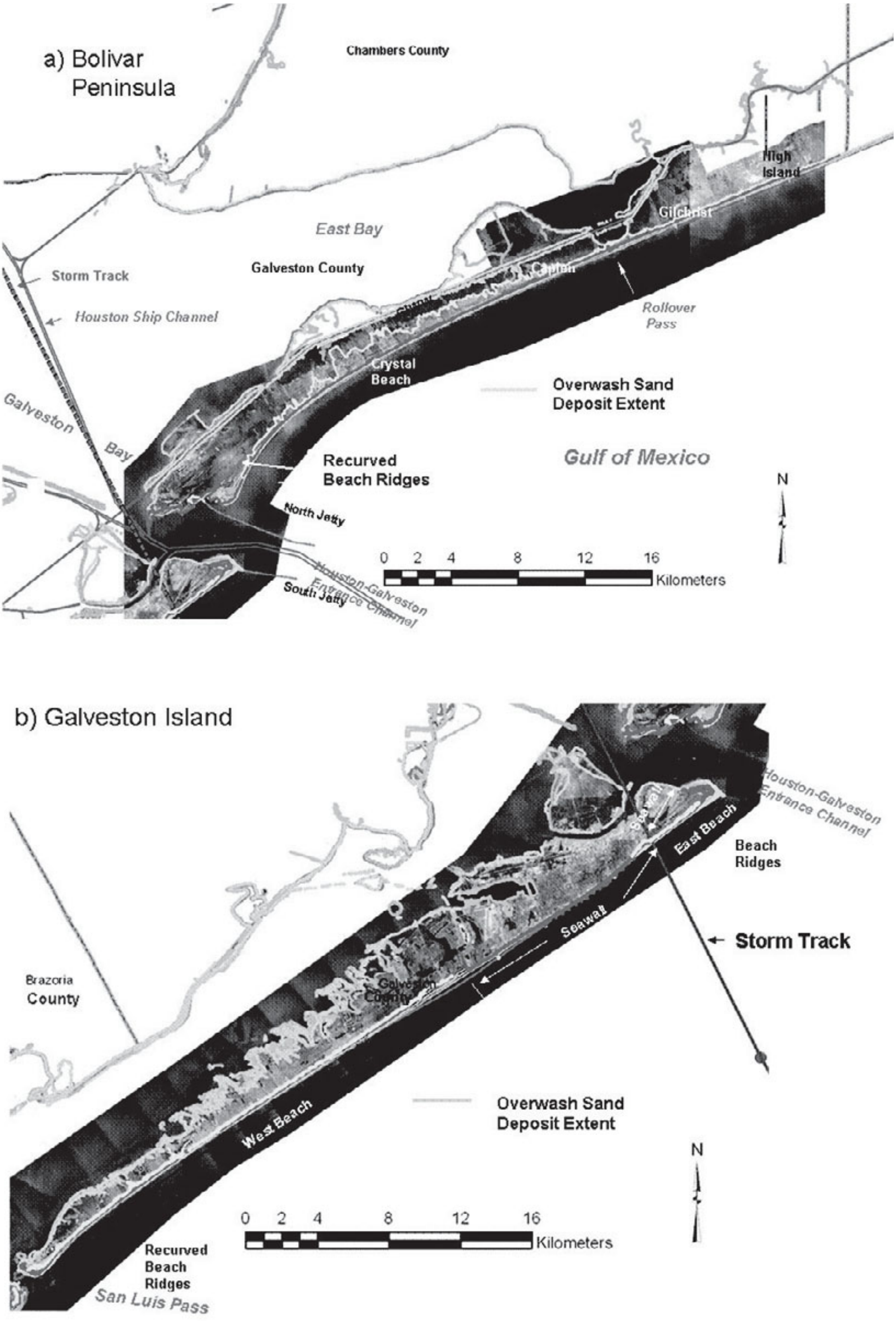


Figure 4-15. Overwash sand deposits (a) edge of fan at Gilchrist, (b) edge of fan at Crystal Beach, (c) filling of canal by overwash deposit at Crystal Beach, (d) overwashed sand north of Highway 3005 on West Beach, Galveston Island, (e) overwash bisecting Highway 257 west of Treasure Island, and (f) overwash bulldozed back over rock seawall at Surfside. Arrows show direction of sand flow


a) Bolivar Peninsula
Chambers County
High Island
Gilchrist
East Bay
Galveston County
Caplen
Storm Track
Houston Ship Channel
Rollover Pass
Crystal Beach
Overwash Sand Deposit Extent
Galveston Bay
Gulf of Mexico
Recurved Beach Ridges
North Jetty
N
0 2 4 8 12 16
Kilometers
Houston-Galveston Entrance Channel
South Jetty
b) Galveston Island
Houston-Galveston Entrance Channel
Seawall
East Beach
Beach Ridges
Seawall
Storm Track
Brazoria County
Galveston County
Overwash Sand Deposit Extent
West Beach
N
0 2 4 8 12 16
Kilometers
Recurved Beach Ridges
San Luis Pass

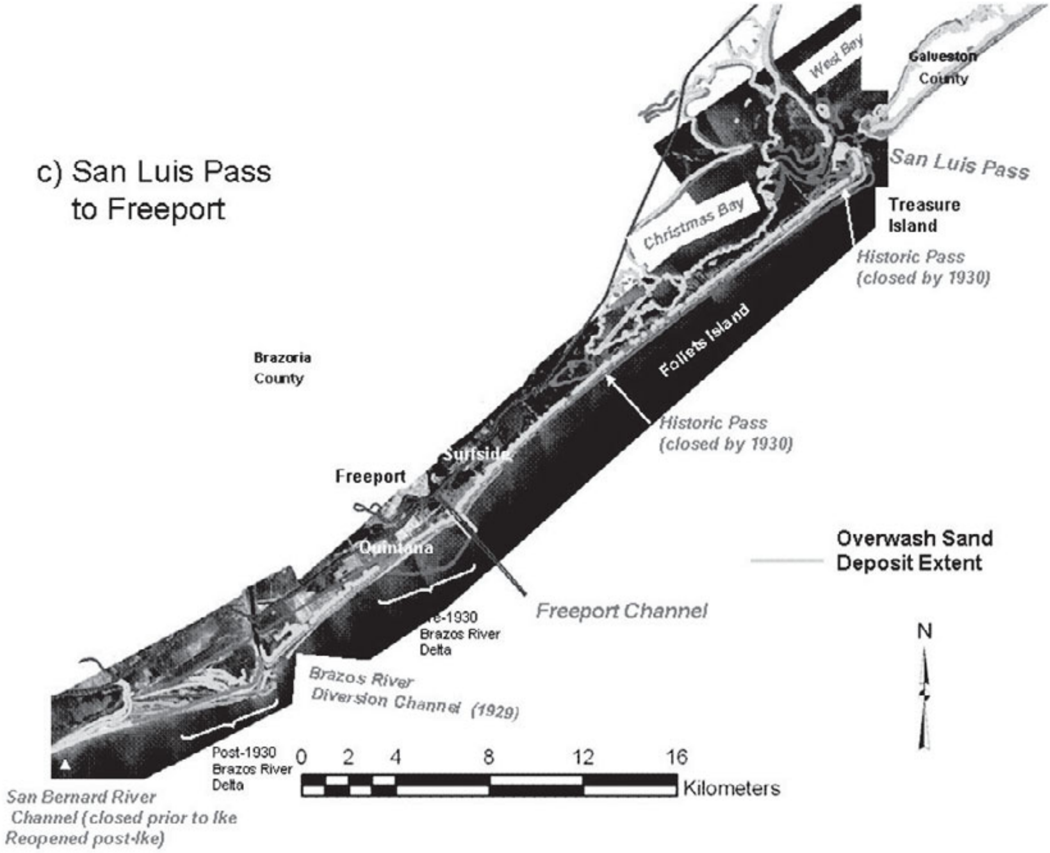


Figure 4-16. Map of the extent of overwash sand deposited (a) on Bolivar Peninsula, (b) Galveston Island, and (c) between San Luis Pass and Brazos River Diversion Channel. Source: Texas General Land Office

Landward transport of sand as overwash was observed in Brazoria County from San Luis Pass to Freeport. There were measurable overwash sands from Freeport to the Brazos River Diversion Channel. The landward extent was measured on the aerial photography 100 to 150 m inland, even though this area is some 60 to 80 km southwest of the center of circulation. Texas Highway 257, which runs along the coast from Treasure Island to Surfside, was bisected in several places as the sand was transported inland over and through the roadway making it impassable (Figure 4-15e). At Surfside, sand was transported over the rock revetment that runs along the beach and inland some 100 m. Figure 4-15f shows the sand that was removed from Beach Drive and deposited back over the rock revetment three weeks after the storm. Overwash deposits were mapped from Treasure Island to just east of the Brazos River Diversion Channel (Figure 4-16c). This area was on the left front quadrant as the storm made landfall. The overwash was measured to be about 100 m inland on average along this section of coast. To the left of the storm track, the overwash was even greater.

Winds Related to Geomorphic Changes

Some of the variability in the extent of damage and change in the geomorphology and structural damage can be explained by a review of the wind fields as Hurricane Ike made landfall. As the storm approached the coast, its right front quadrant had the forward momentum of the storm surge and the wind field. This impacted the area from Bolivar Peninsula to Cameron Parish, La.

Storm surge and waves would be expected to be large in this area. The maximum onshore wind velocities approached the coast just to the east of Rollover Pass. The left front quadrant passed over Galveston Island and extended to the Brazos River Diversion Channel as shown in Figure 3-2. The maximum wind velocities heading offshore were between San Luis Pass and Freeport Channel. The storm surge and waves were reduced by the opposing forces of onshore waves and surge and offshore winds. This is evident in the reduced landward distance of overwash sand transport on the west side of the eye at landfall.

Just after landfall, the wind fields showed a similar pattern with the maximum onshore winds (41 to greater than 44 m/s) occurring between Sabine Pass and Rollover Pass. The eye passed over East Beach on Galveston Island. The maximum offshore winds (33 to greater than 39 m/s) occurred between San Luis Pass and Freeport Channel. The maximum overwash sand penetration was found around Crystal Beach within the high-velocity winds. Less sand penetration was found east of Rollover Pass due to lack of sand-size sediments available to transport inland as overwash. However, storm surge debris evidence supports possible surge penetration up to 20 km inland in Jefferson County in the vicinity of maximum onshore wind fields and resulting wave and storm surge. Post-storm drainage of this water resulted in reverse sand transport in an offshore direction and the observed offshore outwash sand deposits in the vicinity of Sea Rim State Park. The observations of beach and dune erosion, overwash sand penetration and shore protection structure damage, and upland building damage indicate that as the storm approached the coast, the surge was high from Freeport Channel to Sabine Pass, with the maximum impacts on Bolivar Peninsula located in the right front quadrant of the storm.

Chapter 5: Shoreline Structure Issues

This section presents the observations of the two teams on the coastal structures observed along the shoreline, including offshore pier, erosion control structures, and jetties. The majority of the observations are derived from the Galveston County because this area contained the most structures.

Piers

Prior to Hurricane Ike, there were 11 piers along the upper Texas Coast from Jefferson County to Surfside. Table 5-1 summarizes the original length of each pier when it first appeared on the historic shoreline data, the pier length measured from the 2006 pre-storm photography, and the post-storm length measured from the 2008 aerial images. Most of the piers were shorter than originally constructed. The shortening was most likely due to past storm activity. The length lost during Hurricane Ike was measured from the 2008 post-storm photography. The two active fishing piers on Bolivar Peninsula were completely destroyed by the storm and only the pilings were left. Six piers were located along the seawall in Galveston. Some were of wooden pilling construction; others had concrete piers, and some were attached to groins. The wooden pier at 21st Street was completely destroyed. Two amusement/restaurant piers at 22nd and 23rd streets built on concrete piers were heavily damaged and completely destroyed, respectively. Most of the debris from these three piers was washed up onto Seawall Boulevard.

A fishing pier built on the gulf end of one of the groins at 61st Street was completely destroyed by the storm. The groin was intact, but the concrete top surface was damaged. A wooden fishing pier at 89th Street survived the storm but lost 251 m of its outer end. All that remain are a few pilings at the outer end. Two fishing piers in Brazoria County also had heavy damage along with a house on a pier at San Luis Pass. The fishing pier at Treasure Island on the west side of San Luis Pass lost 202 m of its outer end, and the shore access ramp was gone. A pier with a house to the south of the fishing pier along the pass's marginal flood tidal channel and the fishing pier near Surfside were also completely destroyed. Most of these piers within the study area had been shortened from their original length by past storm events prior to Hurricane Ike. Post-Ike, all suffered major damage or complete destruction from the waves and storm surge.

89th Street Fishing Pier

The fishing pier is located near 89th Street in Galveston. The total length was about 340 m. The segment between 125 and 310 m from the seawall was lost as shown in Figure 5-1. The two-story building on the pier located near the seawall was heavily damaged, and the first floor was completely lost. These damages were mainly caused by the uplift and horizontal wave forces inside the surf zone.

It seems that the end of the pier remained because it was located outside the surf zone. The first girder attached to the seawall was also damaged as shown in Figure 5-2. The uplift force of the wave in front of the seawall is assumed to have hit the girder. The concrete decking panels were lifted upward by the waves and fell through the girders onto the beach or seafloor.

Table 5-1. Piers in the Survey Area

Location	*Original Length (m) – (Date)*	*Pre-Storm (5/06) Length (m)*	*Post-Storm (9/15,18/08) Length (m)*	*Length Lost (m)*
Bolivar—High Island	482 (1974)	128	0	Destroyed pilings only
Bolivar—Gilchrist	290 (1982)	128	0	Destroyed pilings only
Galveston Seawall at 21st Street	173 (1965)	173	0	Destroyed pilings only
Galveston—Building on piles in front of seawall 22nd Street	Width – 77 (1965)	Width – 77	Width – 33	Partially destroyed
Galveston—Building on piles in front of seawall 23rd Street	45 (1974)	45	0	Destroyed pilings only
Galveston—Pleasure Pier 25th Street	342 (1965)	342	342	Some damage to buildings on pier
Galveston—61st Street, pier at end of groin	274 total length Pier 112 (1974)	Pier 82	Pier 0	Groin intact, pier destroyed
Galveston—88th Street	340 (1974)	340	89 (not including some pilings at gulf end)	Destroyed; some pilings still standing
Brazoria—Treasure Island in San Luis Pass	404 (1974)	387	185	Outer pier destroyed, damage to inner pier
Brazoria—Treasure Island House on Pier	41	41	0	Destroyed; some pilings still standing
Brazoria—Surfside	275 (1974)	71	0	Destroyed; some pilings still standing

Figure 5-1. 89th Street fishing pier

Figure 5-2. The girders attached to the seawall were damaged by the deflected waves on the seawall

Flagship Hotel Pier

The 25th Street pier (also called the Pleasure Pier or Flagship Hotel Pier) with a total length of about 350 m was the only pier that remained somewhat intact despite heavy damage after Hurricane Ike (Figure 5-3). However, almost all piles of the 25th Street Pier remained in contrast with those of the 89th Street fishing pier. There are several reasons for the differing damage between the 25th Street (hotel) Pier and fishing pier. The clearance between the sea surface and the horizontal beams of the hotel pier was higher than for the fishing pier. Also there was likely deeper embedment of the piles to support the load of the hotel structure and resist the wave forces. Additionally, the water depth seems much shallower than that at the fishing pier, which would have made the wave height smaller than that under the fishing pier.

As at the fishing pier, the first girder attached to the seawall (Figure 5-4) and the sidewalk behind the seawall near the hotel pier (Figure 5-5) were damaged. It seems that the waves overtopped the seawall, and some material was piped through or underneath it. Additionally, there was damage to the hotel ramp. The uplift forces were greater than the old corroded steel drift pins could resist as shown in Figure 5-6.

Figure 5-3. Flagship Hotel Pier

Figure 5-4. The loss of the first girder of the hotel pier caused by the uplift force of the waves

Figure 5-5. Overtopping wave seems to have caused the leakage of backfill

Figure 5-6. Collapse of ramp onto Flagship Hotel Pier

Wooden Pile Pier

There were two wooden pile piers 250 m northeast of the Flagship Hotel. The smaller clearance between the sea surface and the beams placed high lateral and uplift wave forces on the structure. As a result, the weak wooden structures were destroyed as shown in Figure 5-7. The piles were quite old, and marine borer damage had required several previous repairs.

Seawalls

The change in condition of the seawalls was also examined. Table 5-2 lists the types and linear extent along with the condition changes due to the hurricane for all gulf-facing seawalls found along the study area. Two seawalls at the west end of Bolivar Peninsula were identified from pre- and post-aerial photography. One located in front of Fort Travis was a vertical concrete seawall with a rock revetment for toe protection. Some of the toe protection was moved, and there was damage to the concrete cap, but otherwise, the wall was intact. A rock revetment was also constructed along 697 m of Texas 87 in front of the Bolivar Lighthouse near the ferry dock at the extreme west end of the peninsula. Some of the rock was displaced, but otherwise, the revetment was intact. On Galveston Island, the Galveston Seawall covered the gulf front of East Beach. The vertical curved concrete seawall had a rock revetment at the toe and pocket beaches within each of several groin compartments. Little damage was observed to the seawall in the downtown area except for some displacement of the toe protection. Some of the railings on the beach access stairs were deformed by wave activity and floating debris. Major damage was observed at the west end of the seawall where 80 m of the ramp behind the wall was undermined and collapsed as waves flanked the end of the wall.

Figure 5-7. Wooden piles supporting the pier for the historic Balinese Room

In Brazoria County, a rock revetment and vertical seawall were built to protect homes on the west side of San Luis Pass. A sand spit had grown as the San Luis Pass shoreline accreted. As the inlet channel shifted over time, the homes became vulnerable to erosion (Gibeaut et al. 2003). After Hurricane Ike, many of the rocks were displaced, but the main structure of the revetment and vertical concrete seawall remained intact.

About halfway between Treasure Island and Surfside along Texas Route 257, there was an apartment complex with a vertical concrete seawall. After the storm, a gap was cut in the wall forming a scour channel between buildings. The northeast corner was also cut allowing a scour channel to form on the inside of the tieback wall almost back to the road. The tieback wall was flanked on both sides with backfill scour occurring and damage to the flanking walls.

In the Town of Surfside, a rock revetment was constructed along the gulfward side of Beach Drive and covered with a dune. There were several houses on the beach, gulfward of the revetment/dune. The owners of five of the homes located between Sundial and Crab Streets constructed a vertical metal sheet pile seawall in front of their properties, with a flanking wall on each end. The sheet pile structure was destroyed by the hurricane except for the west flanking wall (Figure 5-8a). The rock revetment along Beach Street was uncovered as the storm washed the dune into the interior as overwash (Figure 5-8a). The sand from this overwash was bulldozed back over the revetment in some places. In others the displaced rock was all that was left after the storm. Most of the houses gulfward of the revetment were destroyed, and several landward of the structure suffered heavy damages (Figure 5-8b).

Table 5-2. Seawall Damages

Location	Type	Linear Extent (m)	Condition Change
Bolivar— Fort Travis	Concrete wall with stone revetment	1,250	Some damage to concrete cap
Bolivar— Texas 87 at Lighthouse	Stone revetment	697	Minor damage
Galveston Seawall	Concrete w stone toe	15,700	Damage to toe protection Damage to 90 m at west end
Galveston Island— Sea Isle	Vertical walls: Concrete Wood	558 110	Bisected and some sections leaning over
Brazoria— Treasure Island	Rock revetment and concrete seawall	512	Rocks moved and gaps in wall
Brazoria— Apartments between Treasure Island and Surfside	Vertical concrete wall	198	Gap in wall
Brazoria— Surfside	Vertical sheet pile wall	150	Collapse, only west-side wall up
Brazoria— Surfside	Rock under dune	1,020	Dune eroded, rock exposed Some rock collapse

Figure 5-8. Damages to coastal structures at Surfside

Effectiveness of Galveston Seawall

The Galveston Seawall and associated raising of the adjacent ground elevations[1] that occurred in response to the devastating 1900 Hurricane were effective in preventing erosion of the upland, and it appears that wave overtopping was modest. Although the highest winds and storm surges were east of Galveston Island, these formidable improvements are credited with the prevention of substantial damage to upland structures. The only substantive damage to the seawall occurred at the western end where the seawall was flanked and erosion occurred behind the seawall. Due to the dominance of high-rise buildings landward of the seawall, which had no water-related

[1] Ground elevations landward of the Galveston Seawall were elevated by approximately 7 ft. through dredging in Galveston Bay.

damage, this report concentrates on small buildings. Figure 5-9 documents damage to the west end on the Galveston Seawall.

Other damage at the seawall occurred from the loss of backfill in some locations causing a failure of the sidewalk (Figure 5-5). The repair of these sections proceeded without appropriate filter materials at cold joints (Figure 5-10). Workers first formed and poured a concrete trough between the highway paving and the cast drainage holes in the top of the seawall. They filled the trough with sand and poured the sidewalk as the top of the drain. Presumably the sand in the trough is washed out after the sidewalk has cured. Many of the problems in the sidewalk were caused by sediment washed out though the various joints between components.

Figure 5-11 shows the condition of the Galveston Seawall before Hurricane Ike. It can be seen that behind the wall is Seawall Boulevard which has a sidewalk on either side. The paved area is in general sloped seaward to allow overtopping water to escape without running through the city.

Stability of the Galveston Seawall

Although the Galveston Seawall apparently performed well during Hurricane Ike, several observations indicate that the seawall might only be marginally stabile during a future major hurricane. Observations during the field investigation suggest that the water level in the backfill behind the wall may have been at a high level, perhaps near the surface, while the water level seaward of the wall was much lower. Elevation of the waterlevel behind the seawall is indicated by failure of numerous locations of the sidewalks behind the seawall (Figure 5-12) where an apparent "piping" failure occurred. The piping failure would have occurred if the hydrostatic water head behind the wall caused migration (piping) of the sand backfill through joints in the wall or along utility trenches or similar pathways causing loss of backfill. It is unlikely that the original design envisioned a condition where the backfill might be saturated when a relatively low water level exists on the seaward side of the wall. The high water level in the backfill would cause a large lateral pressure on the wall when there was a significant differential water level across the wall. If the differential water-level condition develops during another major storm event, two other elements may become critical to the wall's global stability. The water pressure would exert an additional force on the rip rap along the toe of the wall and on the pilings underneath the wall. The pilings were likely designed as axially loaded rather than laterally loaded piles and would, therefore, provide only nominal lateral capacity without detrimental deflection. The stability of the wall could potentially become unstable if a future storm event produces high water behind the wall and also displaces a substantial portion of the rip rap. The stability would be further reduced if the tops of some of the pilings deteriorated near the connection between the pilings and the base of the seawall. Numerous cases of severe deterioration of both wood and concrete structural members were observed during the field investigation, but no exposed pilings under the wall were found (Figure 5-13).

To assess the effects of these potential conditions, preliminary analyses of the wall's global stability were preformed as described below. Estimates of pile diameter and spacing were obtained from USACE data (USACE 1981, 1995) and from republished original construction photographs (Hansen 2007). Based on these data, the piles were estimated to be approximately 300 mm in diameter near the tops with estimated spacing of 3 m along each of the four rows.

Figure 5-9. Damage at southwest end of seawall

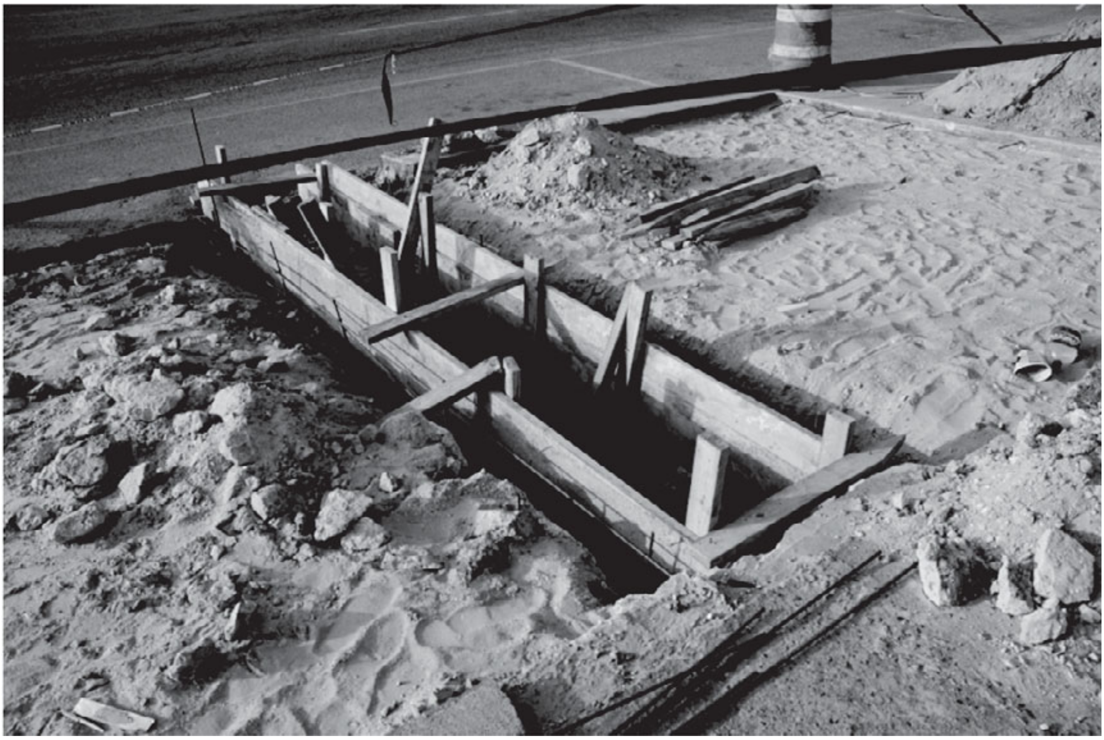


Figure 5-10. Repair of street drains that connect through the seawall

Figure 5-11. Condition of Galveston Seawall before Hurricane Ike

Figure 5-12. Settlement of slabs behind the seawall, potentially caused by piping failures

Figure 5-13. Examples of deterioration of concrete and wood structural members

Preliminary global stability analyses were performed with the two-dimensional limit equilibrium computer program *GEOSTASE* (Gregory 2005) using the Spencer option. Three conditions were analyzed. A total of 500 potential failure surfaces were analyzed for each condition using a random search technique for generating circular surfaces. The water level in the backfill behind the wall was modeled at the ground surface with a lower water level in front of the wall in all three analyses. The first analysis assumes that the pilings have not deteriorated and each pile is capable of providing an allowable lateral capacity of 5 kips and that the rip rap is in place at the toe of the wall. The calculated factor of safety (FS) for this condition is 1.369, or approximately 1.4 (FS values are expressed to three decimal places for relative comparison only. Realistically achievable accuracy should be considered to one decimal place only). This FS value may be marginally acceptable but would be considered low for current standards. The second analysis assumes that the piles are available to provide lateral capacity as described for the first analysis, but the rip rap has been displaced by the storm. The calculated FS value for this condition is 1.116, or approximately 1.1. This FS value would not be considered acceptable and within the margin of error, and it indicates potential failure. The third analysis assumes that the piles have deteriorated at the connection to the base of the seawall or that the sand in front of the piles has been eroded away or severely loosened by the storm, and the piles no longer provide any significant lateral capacity. The third analysis also assumes that the rip rap has been displaced. The calculated FS value for this condition is 0.987, or approximately 1.0, indicating global sliding failure of the wall. The profile plots from the three analyses are presented in Figures 5-14 to 5-16. The circular, solid line in the figures is the most critical surface (lowest FS value) of the 500 analyzed. The circular dashed line is the line of thrust calculated in the Spencer method.

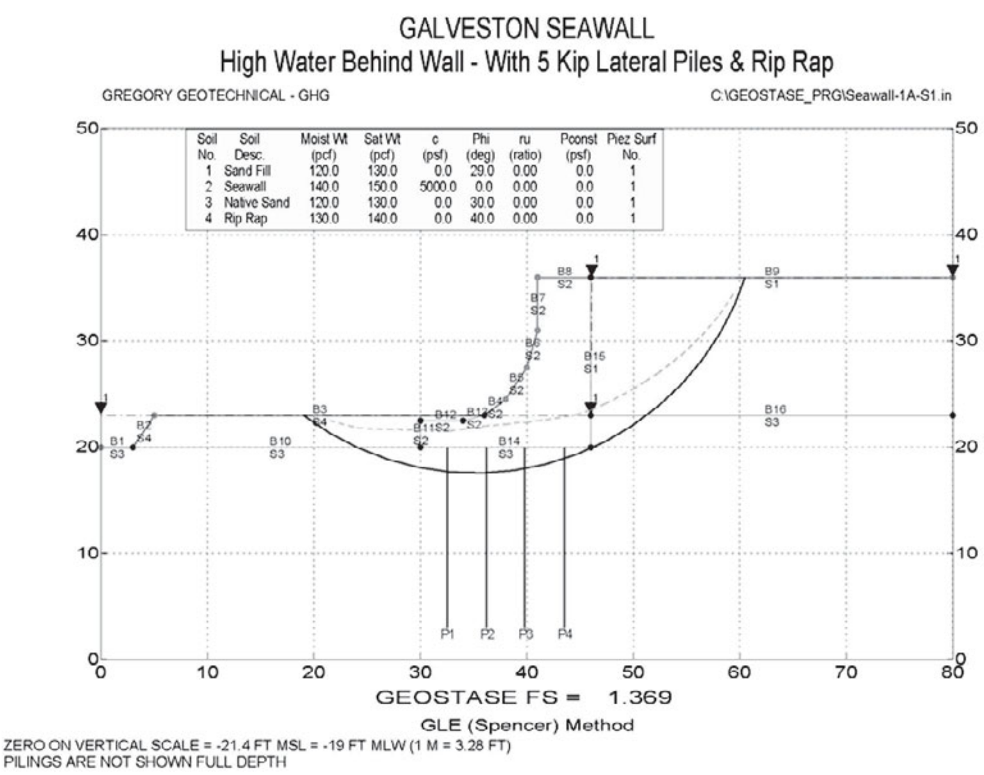


Figure 5-14. Stability analysis for Galveston Seawall with high water behind wall, 5 kip lateral piles, and rip rap toe protection

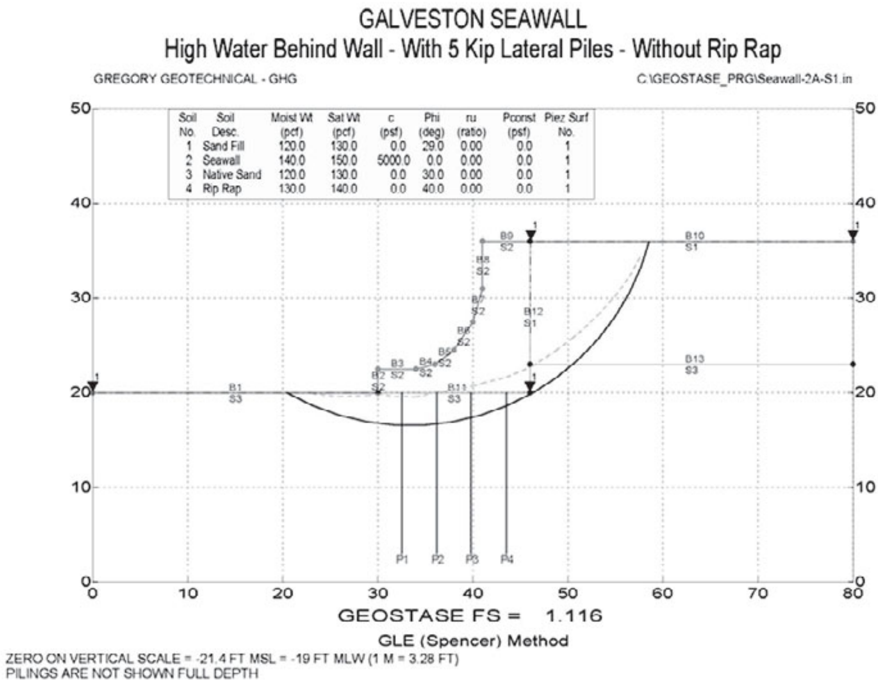


Figure 5-15. Stability analysis for Galveston Seawall with high water behind wall, 5 kip lateral piles, and without rip rap toe protection

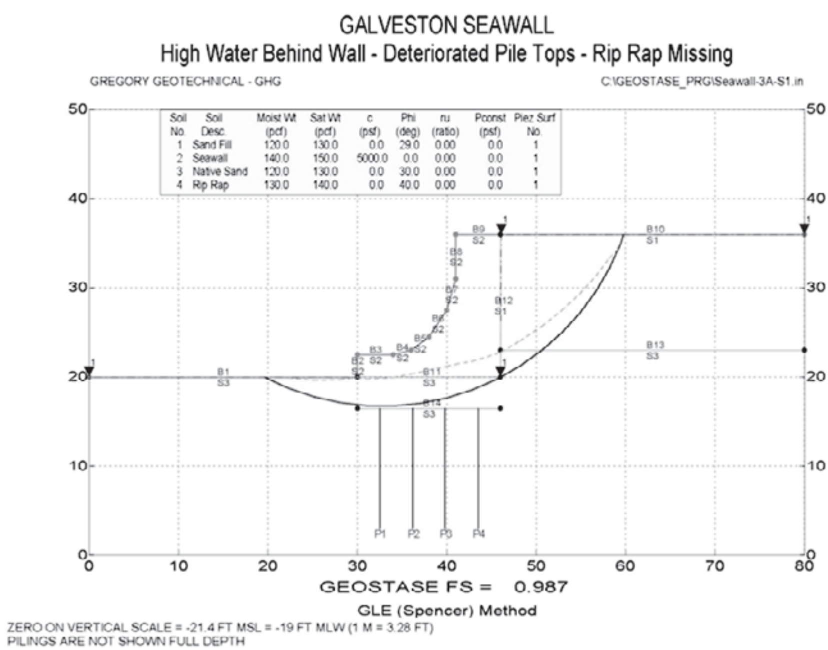


Figure 5-16. Stability analysis for Galveston Seawall with high water behind wall, deteriorated pile tops, and without rip rap toe protection

The stability analyses are very preliminary in nature and are based on estimated values and assumed conditions. Accordingly, the calculated FS values can only be considered as general indicators of the potential stability concerns for the seawall. More detailed information could produce significantly different results. However, the preliminary analyses indicate that the seawall may not have adequate FS values for global stability if the assumed values are reasonably accurate and the assumed conditions are produced in a future storm event. Consequently, the integrity of the rip rap and pilings is of major importance. Steps should be taken to prevent displacement of the rip rap in a major hurricane, and the integrity and lateral capacity of the piles should be verified.

Sand-Filled Geotextile Tubes

Shoreline protection constructed using sand-filled geotextile tubes were installed along two sections of beach along Bolivar Peninsula on either side of Rollover Pass. Four separate geotextile installations were constructed along Galveston Island's West Beach. Details of these installations are provided in Table 5-3. In all installations, a geotextile apron tube was placed at the dune line. A single round, sand-filled tube was placed on top of the apron. The structure was covered with sand serving as the core of a manmade dune. State permits required that the structures remain buried. A 4,000-m long structure was built in Gilchrist and from Rollover Pass eastward. Impacts from the storm included breaches in the linear structure caused by breakage of the tubes and loss of sand. This process created gaps where waves were allowed to flow between the bags and scour out channels into the backshore (Figure 4-6).

Figure 5-17 shows a ground view of the gap and scour channel on the east end of this installation. Most of the tubes were completely exposed as the sand was eroded away by the storm surge. In some cases only the apron was left after the top tube broke open and was washed away. In other cases scour on the gulf side caused the top tube to roll toward the gulf and be partially submerged on the gulf side of the base layer. Similar response occurred on the west side of Rollover Pass in Caplen where that installation was some 4,300 m long.

Table 5-3. Geotextile Tube Installations

Location	Linear Extent (m)	Condition Change
Bolivar—Gilchrist	4,000	Bisected in several places; some tubes broke open with lost sand and some rolled off foundation Beach scoured in gaps
Bolivar—Caplin	4,350	Bisected in several places; some tubes broke open with lost sand and some rolled off foundation Beach scoured in gaps
Galveston Island—West Beach at Boddecker Channel	484	Bisected in two places; some tubes rolled off foundation
Galveston Island—Spanish Grant	1,673	Bisected in several places; some tubes broke open with lost sand and some rolled off foundation
Galveston Island—Pirates Beach	2,480	Bisected in several places; some tubes broke open with lost sand and some rolled off foundation
Galveston Island—Kahala-Pocket Park	182	Intact but exposed; dune cover eroded away

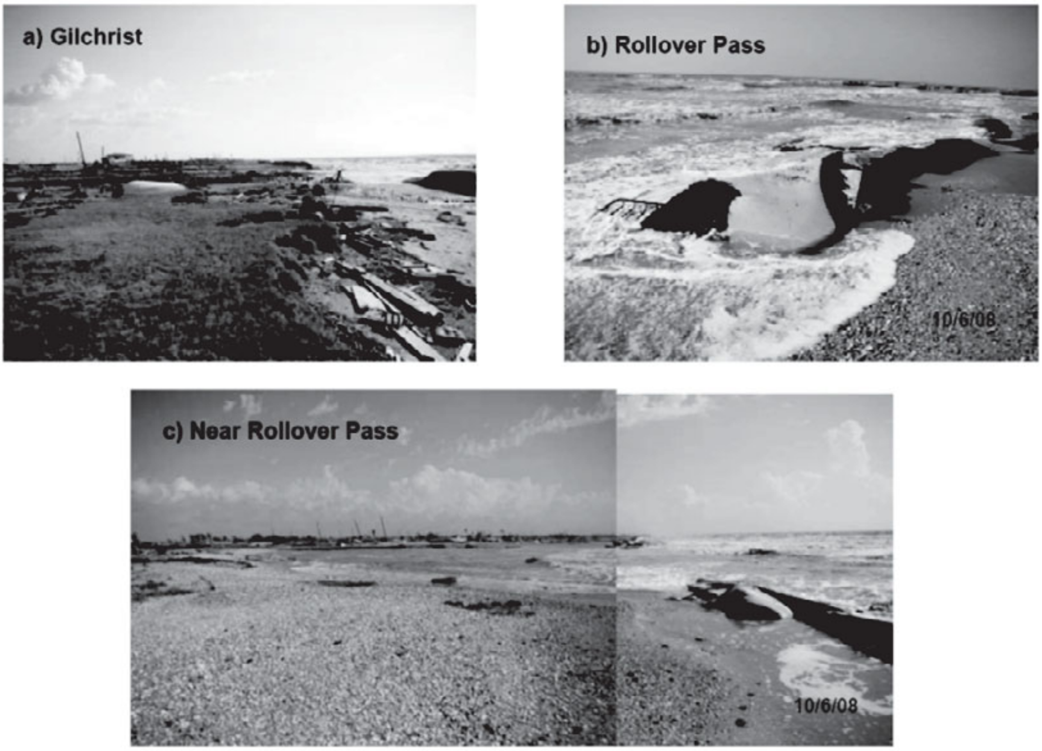


Figure 5-17. Geotextile tube performance on Bolivar Peninsula, (a) at Gilchrist, and (b) and (c) near Rollover Pass, showing shoreline erosion between gaps in structure

All of the geotextile tube installations in Galveston County were on West Beach. The first placement was in front of condos at Boddecker Channel, just to the west of the seawall. The tubes were intact after the storm but were completely exposed with the dune sand eroded away. A few short gaps were formed and some of the tubes rolled off their apron (Figure 5-18a). A 1,673-m-long linear installation at Spanish Beach was completely exposed and experienced several tubes rolling off their base apron due to gulf-side scour (Figure 5-18b). Several gaps were formed where tubes failed and were deflated. At Pirates Beach, the 2,480-m-long geotextile tube structure suffered much the same fate with cutting and deflation of the top tube, which resulted in a gap and loss of protection (Figure 5-18c). The short installation at a county pocket park near Kahala Beach fared well with little damage to the geotextile tube structure, but all the dune sand placed over the structure was eroded, completely exposing the geotextile structure (Figure 5-18d).

Groins

As part of a demonstration of innovative shore protection under the USACE National Shoreline Erosion Control Development and Demonstration Program, six groins constructed of sand-filled geotextile tubes were placed perpendicular to the shoreline along the beach in Jefferson County. These geotextile groins were about 50 m long and placed from the back beach vegetation line toward the gulf. Each groin compartment had a different configuration of dune or beach fill with mixed sediments of clay core and sand. The six geotextile groins all had failures due to breakage during the hurricane, and all deflated and lost their form and function.

Two stone groins are located at the Bolivar Peninsula Ferry Dock. These groins define the edges of the ferry terminal. The southern groin is constructed of cut red granite, and the northern groin is sheet pile. Both experienced only minimal damage (Figure 5-19a).

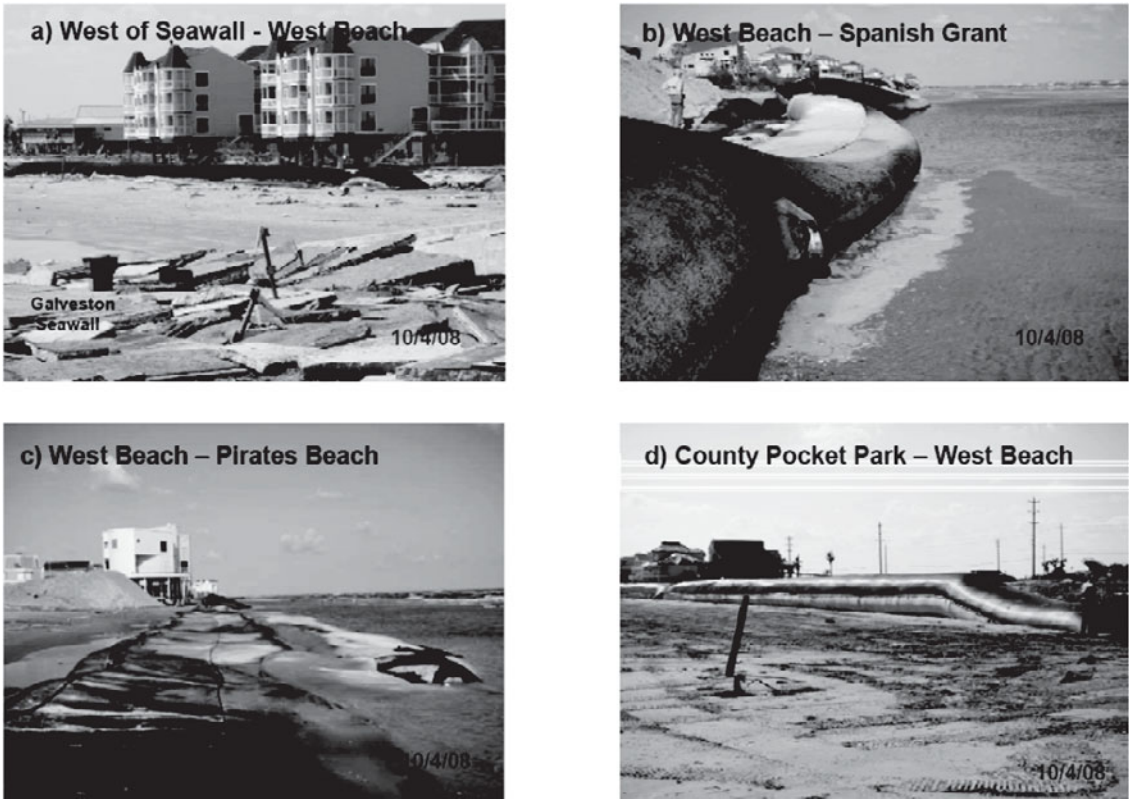


Figure 5-18. Performance of geotextile installations along Galveston Island, (a) just west of Galveston Seawall with gaps and exposed from erosion of dune, (b) at Spanish Grant showing collapse of top tube Gulfward, (c) cut and deflation of top tube leaving only base layer, and (d) intact but uncovered tube at Galveston County pocket park near Kahala Beach

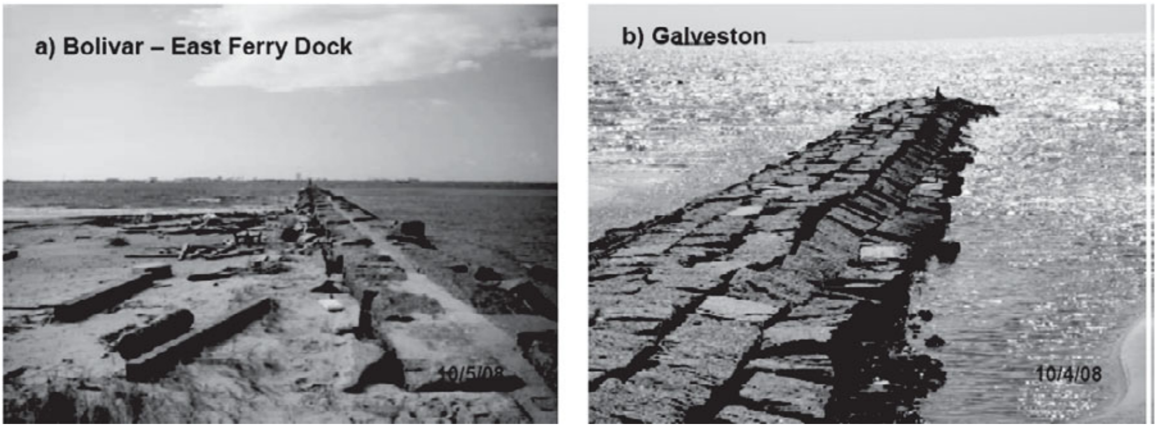


Figure 5-19. Groins at (a) Bolivar Peninsula and (b) along the Galveston Seawall showing little damage

Table 5-4. Observed Damage to Groins

Location	Type	Linear Extent (m)	Condition Change
Jefferson Co.	6 sand filled tubes	50	All tubes cut and deflated one destroyed
Bolivar—Ferry Dock	1 rock	257	Minimal damage
	1 sheet pile	214	
Galveston Seawall—10th Street	Rock, concrete cap	190	Damage to seaward end and concrete cap
16th Street	Rock	155	Minimal damage
21st Street	Rock	157	Minimal damage
24th Street	Rock	148	Minimal damage
28th street	Rock	151	Minimal damage
30th Street	Rock	188	Minimal, rocks displaced and concrete cap damaged
33rd Street	Rock	154	Minimal damage
37th Street	Rock	183	Minimal, rocks displaced and concrete cap damaged
39th Street	Rock	154	Minimal damage
Fort Crockett (43rd Street)	Rock	158	Minimal damage
(47th Street)	Rock	153	Minimal damage
San Luis Resort & Spa	Rock	159	Minimal damage
53rd Street	Rock	158	Damage, armor stone displaced
58th Street	Rock	98	Minimal damage
61st Street	Rock	162	Damage to seaward end and concrete cap

The only other use of groins was on East Beach in Galveston where 15 groins were constructed perpendicular to the Galveston Seawall. All of these groins were cut stone (Figure 5-19b). Four of them had a concrete cap to allow walking access on the groin. Table 5-4 summarizes the damage visible in the aerial photographs. Most of the groins had minimal damage. The concrete caps on groins, consisting of smaller stone, did not fare as well. All of the groins caps were damaged, and some of the rocks were displaced at the gulfward end or along the water line.

Some of the stones were also dislodged as shown in Figure 5-20. These stones were picked up by the waves and were displaced to lower levels, leaving a void in the crest of the groin. The stone appeared to be 3 to 5 ton granite.

Inlet Jetties

All of the inlets along this coast are stabilized by two jetties, except for San Luis Pass. Table 5-5 lists the type of jetty construction, linear extent, and condition change due to the storm. The long Sabine Pass jetties could not be assessed due to lack of post-storm photography coverage. Rollover Pass had short U-shaped jetties on the gulf end of the pass composed of vertical concrete walls with a rock revetment as toe protection. A metal sheet pile wall was extended into the gulf (Figure 4-6). Storm impacts included loss of sand from between the U-shaped jetties on both sides of the pass. Although the vertical concrete wall with toe protection seemed to survive, the

Figure 5-20. Loss of armor stone from 53rd Street groin fronting the Galveston Seawall

Table 5-5. Inlet Jetties

Location	Type	Linear Extent (m)	Condition Change
Sabine Pass—West Jetty	Stone	~3625	unknown
Rollover Pass East Jetty	Concrete wall w/ stone revetment, metal sheet pile section on gulf end	33 U shaped	Intact but loss of sand in U section, metal sheet pile section damaged
Rollover Pass West Jetty	Concrete wall w/ stone revetment, metal sheet pile section on gulf end	90 U shaped	Intact but loss of sand in U section, metal sheet pile section damaged
Houston-Galveston Channel Entrance—North Jetty	Stone	7,478	Minimal damage with displacement at landward end
Houston-Galveston Channel Entrance—South Jetty	Stone	7,400	Minimal damage
Freeport Harbor Entrance East Jetty	Stone, concrete cap	1,330	Minimal damage
Freeport Harbor Entrance West Jetty	Stone, concrete cap	1,444	Minimal damage

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Figure 5-21. Inlet jetty response to Hurricane Ike (a) at Rollover Pass showing deterioration to sheet pile wall and erosion of sand and (b) at Freeport Channel where only railing damage was observed

sheet metal walls were in poor condition, probably from before the storm (Figure 5-21a). The jetties at the entrance to the Houston-Galveston Channel that are longer than 7,000 m are composed of stone. The jetties had low freeboard and appeared to be in relatively good shape after the storm. The north jetty had minor damage and displacement of rock at the landward end where it crosses the shoreline. There was limited coverage of the jetties in the post-storm photography on the outer end, so no damage assessment could be made. The Freeport Entrance Channel had two rock jetties with a concrete cap, which is used as a fishing pier. The missing metal tube railing is the only visible sign of damage in the post storm photos (Figure 5-21b). The post-storm photos do not extend to the outer end of the jetties, so no assessment could be made of the gulfward tips. Minimal damage was observed on either jetty where there was post-storm coverage.

Chapter 6: Buildings

Post-storm damage surveys serve to confirm expected performance in extreme conditions as well as to evaluate recent development trends and conditions unique to each storm. Hurricane Ike confirmed many previously reported observations. In addition, new observations are described for composite foundation performance, and a new method to estimate peak wave and storm surge elevation using building damage observations is described. Most of the buildings in the highest risk areas near the gulf and bays were wood-frame, single-family houses and are the focus of this section. Larger buildings were either more distant from the gulf or protected by the Galveston Seawall.

Wind

Peak wind speeds appeared to be below design levels in the areas inspected. Minor wind damage to buildings was widespread, but serious structural damage was rare with a few exceptions as shown in Figure 6-1. Damage to roof coverings, often one of the most damage-prone components, was common but not uniformly present, as observed in other recent high-wind hurricanes. Many flood damaged buildings appeared to be undamaged by the wind. Most inspections were restricted to exterior observations, but a few interviews with property owners revealed wind-blown leaks in the building envelope that were not associated with structural damage, a common observation following prior storms.

Wind damage to the single-family houses along West Beach appeared to be much less severe than that observed following Hurricane Alicia in 1983 (Rogers et al. 1985). The likely differences are somewhat lower wind speeds across that specific shoreline; prior damage to the older, most wind-sensitive buildings; and post-Alicia improvements in general construction practice, building codes, and inspections.

Figure 6-1. Partial roof deck failure due to wind uplift

Stillwater Flooding

Evaluation of the storm surge elevations will require more detailed analysis, but the team's observations support preliminary reports that most of the Gulf of Mexico shoreline from East Beach west to Surfside had flood elevations below the design requirements described in the most recent flood maps. The common construction practice of elevating houses on shallow piling foundations, with underhouse parking or storage in some cases, effectively provided freeboard above the required elevations. As expected, low-elevation buildings subject to stillwater flooding got wet across the entire study area along with anything stored in the underhouse enclosures.

Initial watermark reports indicate that water levels on the Bolivar Peninsula were below the predicted flood levels except for High Island and some of the surrounding eastern sections of Galveston Bay. USGS storm surge gauge reports and observations of wave damage elevations for this study suggest that water levels exceeded floodmap levels for much of the peninsula. Beyond the stillwater flood damage, the primary cause of severe structural damage was wave damage near the gulf and around the larger bays.

Wave Damage

Storm surge and wave elevations caused increasing frequencies of structural damage along the gulf shoreline from the Galveston Bay jetties east along the Bolivar Peninsula to the end of the development near High Island. Most of the buildings were single-family houses. Once the wave elevations exceed an open piling foundation elevation, severe damage occurs quickly. The floor systems of most houses are highly susceptible to failure after only a few waves. The typical results leave nothing but the pilings or, with shallow piles, total removal of the building. A section of homes considered total losses due to wave damage extended several blocks wide along the east end of the peninsula as shown in Figure 6-2. Farther landward, damage gradually reduced in severity, evidenced by decreasing levels of breakaway wall failures, which suggests a likely gradual drop in wave height. Farther west around Gilchrist and Rollover Pass where the landform narrows, losses of buildings across the peninsula approached 100 percent, and wave damage was apparent across the entire peninsula. The common characteristic of the surviving and partially remaining houses was an open, piling foundation with a higher floor elevation. The remaining empty pilings suggest that lower elevation houses disintegrated or were washed into the bay. Preliminary analysis of building wave damage elevations based on LIDAR ground elevations suggest that wave crests reached elevations of +5.5 to +6.2 m NAVD and 0.5 to 1.2 m above the minimum floor elevation requirements on the flood maps in effect at the time of the storm. Many houses constructed at the minimum elevation requirement were also destroyed in the storm.

Erosion Damage

As noted previously, the entire study area has low ground elevations and dunes. Compared to most shorelines along the Gulf of Mexico and Atlantic Ocean, it has more underlying fine sediments than typical barrier island sands. Erosion damage to building foundations was observed from two causes: wave-induced retreat of the shoreline and localized scour as the storm surge moved over the flooded landform. The shoreline erosion affected the first row or two of buildings from West Beach to Surfside and along the Bolivar Peninsula. The seawall along East Beach and the prior accretion west of the Galveston jetties prevented erosion in the central area.

(a) (b)

Figure 6-2. Building survivors and failures on the Bolivar Peninsula. The first two rows experienced erosion landward of geotextile tube. More landward buildings were destroyed by waves. Surviving buildings, circled on left side of (b), had higher floor elevations. Source: Houston Area Council and NOAA images

The localized scour was highly irregular across the developed areas. Scour frequently appeared to be deeper around foundations, likely due to increased turbulence and/or ground-disturbing activities associated with the original construction. Observed ground disturbances included auger installation of shallow piling foundations and the replacement of originally consolidated clays with unconsolidated material around the building footprints (Figure 6-3). Often the scour appeared random but was likely affected by local sediment variations in addition to buildings, roads, canals, and other surface structures (Figure 6-4). Not surprisingly, localized scour was more likely closer to the gulf or bay shorelines and was more widespread where the landforms were narrowest, as observed near Rollover Pass. The erosion patterns suggested both onshore and offshore flow on the Bolivar Peninsula. In Surfside, the scour appeared to be from predominately offshore flow, as expected from the offshore winds of the left quadrant of the hurricane.

Figure 6-3. Localized scour engulfing the full footprint of the short pile foundation

Figure 6-4. Local sour at the corner of the ground slab

In areas of Surfside, several adjacent houses were damaged by differential settlement of the foundations (Figure 6-5). The scour surface suggested that thicker layers of the fine sediments were a contributing factor. Prior to Hurricane Ike, the City of Surfside Beach required wooden pilings to be a minimum of 4.9 m. This resulted in an embedment depth of 1.8 to 2.4 m. Erosion depths at the houses ranged from 1.2 to 1.5 m. The houses were apparently constructed with ground supported concrete slabs underneath the elevated houses. The slabs were used for parking and for patio areas. The slabs were placed in large sections with few joints and virtually no joints that penetrated the full depth of the slabs. The slabs were also poured in intimate contact with the wooden pilings and, in some instances, were attached to the pilings with steel dowels. A substantial portion of the pilings' foundation bearing capacity was likely from side resistance (skin friction) along the embedment depth of the pilings. Most of the pilings were about 250 mm square. The relatively small end area of the pilings would have provided a relatively small part of the total bearing capacity. When a majority of the embedment depth of the pilings eroded away, most of side resistance portion of the bearing capacity was lost. Moreover, the slabs, which were largely ground supported prior to the storm, transferred most of their load to the pilings in areas where the slabs were undermined by erosion. The non-uniform erosion, loss of skin friction, non-uniform additional slab loads placed on the pilings, and non-uniform soil conditions are believed to have contributed to the differential settlement of the structures.

If the pilings had been longer (embedded deeper) a significant amount of skin friction capacity would have remained after the storm. If the slabs had not been attached to the pilings, slab sections would have essentially collapsed as the erosion occurred and would not have transferred their weight to the pilings. If these conditions had all been present, it is likely that the differential settlement and resulting damage would have been prevented. Following Hurricane Ike, the city reportedly changed the piling length requirement to 6.7 m and now requires slabs to be isolated from the pilings and placed in small panels.

Figure 6-5. Differential settlement of houses at Surfside Beach

Both types of erosion resulted in relatively shallow erosion around building foundations, typically up to 1.5 m below grade and, in rare cases, up to 2.5 m. A well-imbedded piling foundation should have prevented erosion damage in those conditions. From West Beach to Surfside, where wave damage was below design levels, shoreline erosion under the first row or two of houses caused widespread failures and was the most common cause of building failure (Figures 6-6 and 6-7). Similar failures in the area were reported following Hurricane Alicia, but there appeared to be little improvement in piling embedment practice (Rogers et al. 1985). In recent years, long-term erosion had placed more than 100 houses on the beach prior to Hurricane Ike. However, with the low ground elevations and flat beach slopes of the area, foundation failures due to erosion would have been easily prevented with an adequately imbedded piling foundation, regardless of the siting of the building (Figure 6-8).

Figure 6-6. Destroyed and floated houses on West Beach primarily due to shoreline erosion around shallow piling foundations. Source: Houston Area Council and NOAA images

Figure 6-7. West Beach building failures primarily due to wave induced erosion of shoreline; minimal damage to elevated buildings farther landward. Source: Houston Area Council and NOAA images

Figure 6-8. Foundation rotation due to inadequate piling embedment

General Building Summary

Small buildings that were adequately embedded to tolerate moderate erosion and sufficiently elevated to avoid wave forces on the floor beams and joists performed well even in the highest exposures near the gulf shoreline, as has been typically observed in previous storms. Breakaway walls under piling-supported buildings generally failed reliably under wave loads without damaging the elevated buildings, except for minor damage where wiring, plumbing, or other utilities for the elevated building were imbedded in the walls.

Composite Foundation Damage

Common practice for piling-supported houses in most areas has been to use continuous individual pilings to support the elevated floor. Timber pilings are most often used. Prestressed concrete and other materials have also been installed. With adequate embedment and floor elevation, performance has been very reliable. For high-rise buildings, it is more typical to use composite piling foundation. Concrete/timber pilings are driven or concrete pilings are augured in place with reinforcing to support a concrete pile cap. The cap supports cast-in-place columns or shear walls that support the elevated floors of the building. Large buildings are typically professionally designed and use highly conservative foundation capacities. Although some foundation damage due to waves and erosion has been observed following hurricanes, no U.S. high-rise building has ever collapsed.

There has been a growing trend to scale down the composite foundation designs for use in single-family houses. A successful application was reported following Hurricane Katrina (FEMA 2005). However, Hurricane Ike exposed several vintages of composite foundations that raise questions on their use in small buildings. Augured, reinforced concrete pilings connected to timber or prestressed concrete columns were in limited use on West Beach prior to 1983 (Rogers et al. 1985). Failures were reported in eroded areas following Hurricane Alicia, and failures in similar pre-Alicia buildings were also observed after this storm. The older designs appeared to be substantially under-designed and usually failed in the augured pile near the cap.

A new subdivision near the east end of the Bolivar Peninsula had recently installed 13 houses on composite foundations (Figure 6-9). Augured concrete pilings were cast with an integral slab-on-grade cap with cast-in-place, reinforced concrete columns to support the elevated buildings. The dimensions and workmanship of the piles, columns, and reinforcing appeared to be much better than those built pre-Alicia. The buildings were located on the north side of the beach road and likely received higher storm surge, wave, and wind conditions than any other buildings in the path of Ike's U.S. landfall. Local scour around the slabs was 0.3 m or less, barely exposing a few of the auger piles, thus, ruling out erosion as a significant stress on the foundation. The lowest, wood-frame floors were well elevated, approximately 6 m above grade, which was sufficient to avoid wave impacts. A wooden deck was bolted to the columns approximately 3.7 m above grade. Three buildings collapsed with column failures at or above the slab level (Figure 6-10). Deck failures in each of the remaining 10 houses suggested that wave heights reached at least a 0.3 m above the deck level but below the elevated floor components. Most of the collapsed and standing columns exhibited tension cracks as closely spaced as 0.15 m in sections up to the deck level. Partial compression fractures at the slab/column connection were also present in two of the remaining foundations (Figure 6-11). The steel reinforcement rods from the auger pile/slab forming the connection to the columns remained in place in the failed buildings. Vertical separation of the steel from the concrete column was apparent where remnants of the columns remained.

Figure 6-9. Surviving composite-concrete foundations on Bolivar Peninsula

Figure 6-10. Composite-concrete foundation column failure at column to slab/pile cap connection

Figure 6-11. Compression fracture at column to slab joint in composite-concrete foundation

The composite foundation has been found to perform well in larger buildings. However, they have significant design, quality-control, and cost limitations when used in small buildings, making them a poor design choice. Pile caps are typically placed at grade, but coastal design guides recommend that they be placed below the predicted erosion depth over the lifetime of the building to avoid lateral forces on the larger cross section of the cap (FEMA 2000). Vertical erosion predictions for individual storms and for long-term erosion over the lifetime of the building are highly variable. Adequately lowering the pile cap to avoid erosion from shoreline retreat and localized scour, even in Ike's moderate erosion conditions, significantly complicates construction because of the depth required below existing grade and potentially below the water table. Underestimating erosion places high wave forces on the larger dimensions of the caps. Even if adequately imbedded, the cap's connection between the pile and column is often the weakest point in the foundation system, yet it is near the point of maximum moment on the foundation. The connection is the most difficult to design and the most likely location for quality control defects.

Where waves and erosion dominate the foundation design conditions, continuous, slender pilings offer substantial advantages. Both timber and prestressed concrete piles have proven to be far more reliable and predictable for small coastal buildings. The recent trend toward composite foundations in small buildings appears to be a step backward in hurricane-resistant construction.

Wave Elevation Estimates From Building Observations

Documenting storm surge and wave elevations during hurricanes is critically important to realistically evaluating the coastal building standards and design methods. Water levels are equally important in accurately modeling storm surge, waves, and erosion in the future and in producing statistically relevant flood maps. Unfortunately, the U.S. coastal gauging system was developed for tide prediction and navigation purposes. Tide gauges routinely fail in higher storm surges and, even when functioning, are not optimally located for documenting storm conditions. As a result, hurricane water levels have typically been documented by post-storm watermark surveys. Survey crews search for stilling-well-type conditions in the back room of a building or a floating debris line created by the peak wave runup. Previous evaluations have identified significant questions in the accuracy of what otherwise appear to be high-quality watermarks (Rogers and Houston 1997). In areas subject to waves and erosion, very few high-quality watermarks can be found anywhere.

This field effort refined a new way to identify peak wave elevations based on building damage that would be a useful addition to standard watermark survey procedures. Previous studies have shown that approximately a 0.5 m breaking wave will destroy wood-frame building walls designed for 200 kph winds. Piling foundations are highly tolerant of the wave forces until the wave crests begin to impact the lowest, shore parallel component of the elevated foundation, typically the floor joists in wood-frame house construction. In highly exposed coastal houses, the floor joists appear to begin to collapse as soon as the waves clip the bottom of the joists. By that time, waves are much higher than 0.5 m. The lateral wave forces compact the floor joists landward along the top of the floor beams (Figures 6-12 and 6-13). By the time the wave elevation reaches the top of the floor joist, wave uplift has separated the floor decking from the joists. Higher waves quickly destroy the building or at least leave clear evidence of their damage to the exterior and interior walls.

Figure 6-12. (a) Damage to house floor joists; (b) close-up of floor joists compressed by wave impact

Figure 6-13. (a) Damaged house; (b) left to right, missing floor joists, displaced joists, compressed joists, and original joist spacing

Where shore-parallel floor joist compaction is observed and floor uplift failure initiated without obvious wave damage to the higher walls, it is reasonable to assume that the peak wave elevation was somewhere between the top and bottom of the floor joist. By measuring the distance from the post-storm ground elevation to the joists, various wave theories can be used to calculate the storm surge elevation without waves. Given the high uncertainties in the process, it is reasonable to use depth-limited, linear wave theory to predict the water level. The same methods presently are currently used by FEMA (2000) to predict wave elevations from the predicted storm surge to map for base flood elevations on Flood Insurance Rate Maps.

Wave elevation above grade = 1.55 × storm surge depth above grade

The specific elevations relative to NAVD for storm surge and wave height can then be either surveyed from local benchmarks or determined from as-built elevation certificates typically on file with the local building inspector for recently constructed buildings.

The method was first developed during USACE post-Ivan building damage surveys in Alabama. Three pairs of similarly damaged houses were documented, but adjacent, slightly higher buildings were undamaged. No follow-up elevations were produced for that event. The post-Katrina MAT report (2006) used the method to estimate storm surge and wave elevations on the west end of Dauphin Island, Ala., where no other watermarks were found. One damaged building was identified. Elevations were determined from an elevation certificate and confirmed by certificates for a couple dozen higher and lower neighboring houses. This study documented four similarly damaged houses on the Bolivar Peninsula. The houses were typically on the first surviving row of buildings along the gulf shoreline, previously the second or third row. Elevations have been estimated from a 2006 LIDAR survey and forwarded to FEMA and local authorities for more accurate elevation surveys.

Estimated peak wave crest elevations for the four houses ranged from +5.5 m to +6.2 m NAVD. That would suggest storm surge (stillwater) elevations of +4.3 m to 4.9 m NAVD and estimated wave heights under the buildings of 2.4 m to 2.8 m, well above the 0.5 m threshold for wall failure in breaking waves.

Training watermark survey crews to search for the specific damage patterns in buildings appears to offer an improved understanding of storm surge and wave elevations in areas where high-quality post-storm watermarks are difficult or impossible to find.

Many building were destroyed by Hurricane Ike, particularly on the Bolivar Peninsula. The observed features that separated the survivors from the failures mirrored other recent storms. Piling foundations must be adequately imbedded to tolerate local erosion conditions, and the horizontal building components must be sufficiently elevated to avoid all breaking wave height elevations (Figure 6-14). The primary safety factors are deeper piling embedment and added floor elevation beyond the minimum requirements.

Figure 6-14. Recently constructed Bolivar Peninsula houses elevated more than 2 ft. above minimum required elevation that had minimal damage to elevated structures

Chapter 7: Lifelines and Infrastructure

Lifelines and infrastructure incurred significant damage in numerous locations. However, major infrastructure facilities performed much better than residential structures during Hurricane Ike. The major infrastructure facilities are farther from the beachfront in most cases and are supported by heavy foundations. The major structures typically have more storm-resistant construction than the residential structures. Some of the lifelines and infrastructure facilities observed by the investigation team are discussed in this section.

Power

Widespread power loss occurred during the storm. One of the most significant factors was the lateral failure of power poles supporting the overhead power lines. The combination of saturated soils, wind, and the storm surge resulted in the loss of lateral support, and many overhead power lines failed as a result (Figure 7-1). Erosion uncovered and damaged underground power lines in a few locations, but buried power lines apparently survived the hurricane with little damage for the most part. Deeper pole embedment may have saved some of the overhead power lines.

Figure 7-1. Overhead power line damage on Highway 87, Bolivar Peninsula

Ferry Terminals

Although a large amount of debris was deposited around the Bolivar Ferry Terminal, the loading structures and harbor apparently experienced only minor damage, and reportedly, the terminal was partially operational shortly after the hurricane (Figures 7-2 and 7-3). However, extensive damage occurred to some of the ancillary facilities, such as the pavilions and adjacent restroom building (Figures 7-4 and 7-5).

Figure 7-2. Minor damage to main facilities at the Bolivar Ferry Terminal

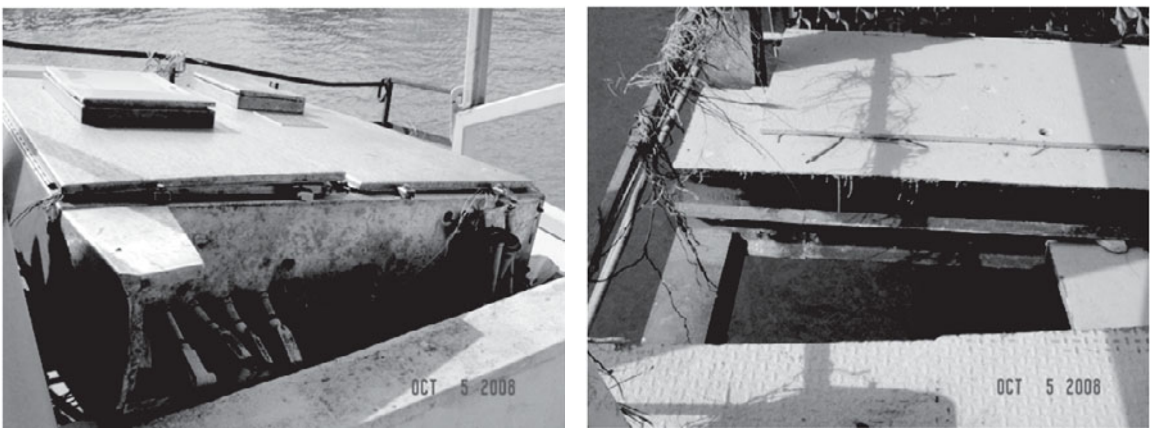

Figure 7-3. Minor damage to main facilities at Bolivar Ferry Terminal

Figure 7-4. Storm debris and displaced rip rap stone at Bolivar Ferry Terminal

Figure 7-5. Extensive damage to pavilions and restroom facilities at Bolivar Ferry Terminal. Billy Edge, Ph.D., and Paul Work, Ph.D., are shown in top photo.

Roads

The investigation team observed extensive roadway pavement failures in numerous beachfront locations (Figures 7-6 to 7-9). Most of the pavement failures were caused by erosion of the base materials and uplift of the pavement surfacing during the surge. Some wearing surface was stripped from some of the roadways. This was specifically observed along the Galveston Seawall where waves overtopped the seawall with a very high velocity.

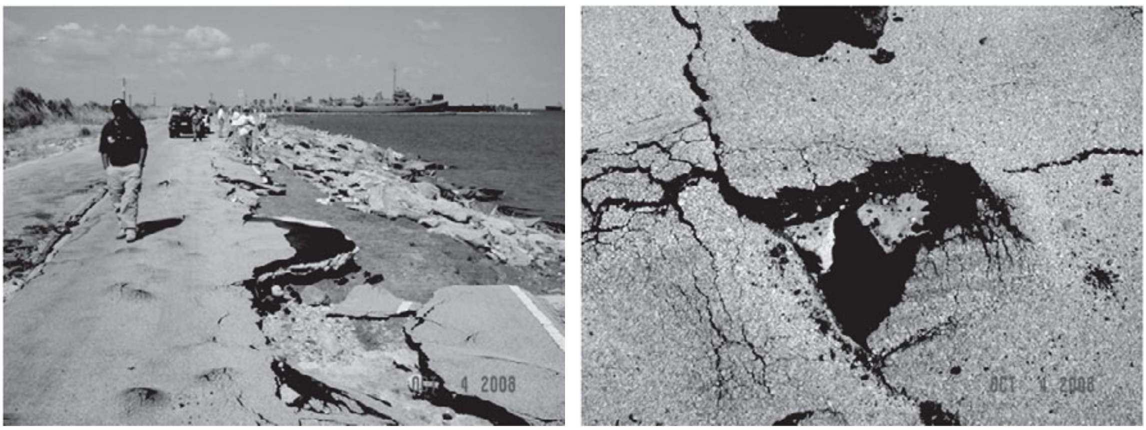

Figure 7-6. Pavement damage on Seawolf Parkway—Pelican Island Seawolf Park. Jeff Waters, Ph.D., is shown in foreground of left photo.

Figure 7-7. Destruction of Residential Roadway—Bermuda Beach near San Luis Pass

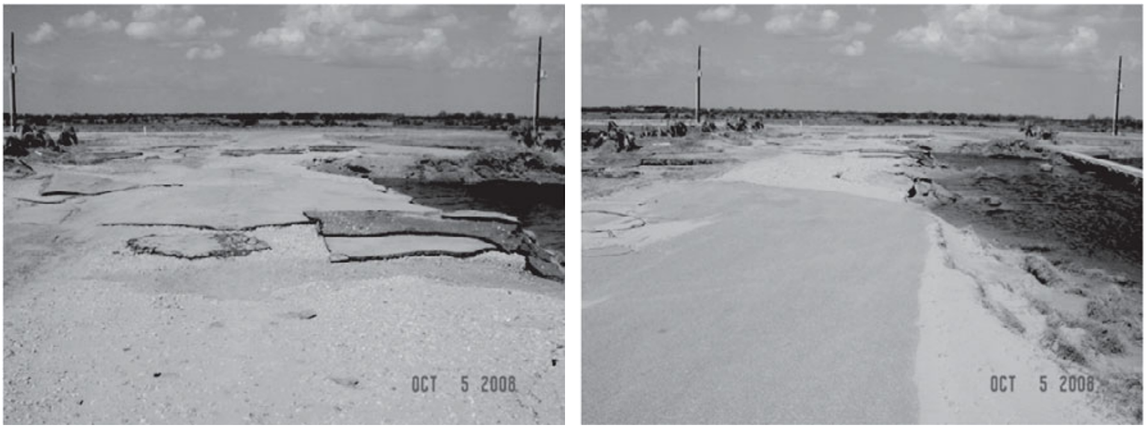

Figure 7-8. Entrance Road Damage—The Biscayne off Highway 87

Figure 7-9. Roadway Damage—Coastal Highway between San Luis Pass and Surfside Beach

Bridges and Wharf Bulkheads

The Highway 87 bridge at Rollover Pass incurred extensive damage and displacement of the bridge deck (Figures 7-10 to 7-14). Amazingly, one outside lane remained sufficiently intact to allow limited traffic flow. The bridge abutments and piers appeared to have suffered little damage. The bridge deck failure was apparently caused by lateral and uplift forces from the storm surge and waves. A sheet pile weir just downstream of the bridge may have contributed to the failure. The deck failure occurred over the bridge piers at the connection between adjacent deck spans. The deck consisted of prestressed concrete panels, which were connected with a cast-in-place reinforced concrete filler beam that connected the adjacent panels and was anchored to the bridge piers with vertical reinforcing steel dowels. The failure mode appears to have been bond failure and stripping of the concrete filler beam from the dowels embedded in the bridge piers.

The team observed several wharf bulkheads along the waterfront where the backfill had been severely eroded during the storm. One such location was at Rollover Pass off Highway 87 (Figure 7-15). The wharf is still vertically standing, but the tie-back anchors were completely exposed in numerous locations due to scour.

Another location where the wharf bulkheads incurred similar scour damage from overtopping was at the Houston Yacht Club (Figure 7-16).

Figure 7-10. Bridge deck damage at Rollover Pass Bridge—Highway 87. Paul Work, Ph.D. and Garry Gregory, Ph.D. (l to r) are shown on the bridge during the investigation.

Figure 7-11. Rollover Pass bridge deck damage

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Figure 7-12. Bridge deck connection filler beam stripped from bridge pier dowels

Figure 7-13. Illustration of bond failure between filler beam and bridge pier dowels

Figure 7-14. Bridge piers intact beneath displaced deck panels. Sheet pile weir in left photo.

Figure 7-15. Scour damage on bulkhead (left) and exposed dead-man anchor (right) at Rollover Pass off Highway 87

Figure 7-16. Scour damage to wooden and aluminum bulkheads at Houston Yacht Club with Billy Edge, Ph.D., shown in right photo.

Water Storage Tanks and Public Buildings

Several water storage tanks, including ground storage tanks and water towers, were observed during the field investigation (Figures 7-17 to 7-21). None of the water storage tanks appeared to have any significant damage except for the steel tank that was apparently being fabricated at ground level when the hurricane struck (Figure 7-17). The damage to the partially fabricated tank occurred prior to the tank being raised to the top of the pedestal. The pedestal did not appear to be damaged. Apparently, the existing ground storage tank on the adjacent property did not experience any significant damage.

An elementary school building, which was nearing completion, and an existing small post office building were observed along Highway 87 on Bolivar Peninsula (Figure 7-22). Based on visual exterior observations, these structures did not appear to have incurred any noticeable damage. It was observed that both were located on top of fill, nearly 2 m above the road surface of Highway 87.

Figure 7-17. Damaged steel water tank on Highway 87 Bolivar Peninsula, which was evidently being fabricated when Hurricane Ike occurred. No apparent damage to pedestal.

Figure 7-18. No apparent damage to ground storage tank adjacent to water tower shown in Figure 7-17

Figure 7-19. Water tower on Tuna Drive at Crystal Beach. No apparent damage to actual tower.

Figure 7-20. Ground storage tank (left) apparently not damaged. Adjacent debris (right) indicates extensive debris trail of storm—Highway 87 Bolivar Peninsula

Figure 7-21. Elementary school (left) nearing completion of construction and existing post office (right) near Highway 87, Bolivar Peninsula. No apparent structural damage.

Water Lines, Sewer Lines, and Utilities

Utility lines appeared to have been damaged mostly in beachfront areas. Many locations experienced damage to septic tanks when a combination of scour and buoyancy lifted and exposed the tanks causing damage to connecting pipes and power cables (Figure 7-23).

Based on local reports, many sanitary sewer lines and manholes were compromised when they were silted in by the storm surge and overwash deposits. Water supply pipelines were damaged in numerous locations where they were exposed by erosion or were connected to other facilities that were damaged (Figure 7-24).

In many cases damage to utilities could have been lessened if appropriate scour and erosion protection had been provided. In other cases, such as the water line on Rollover Pass Bridge, the damage could only have been prevented if the bridge deck had been protected from failure.

Figure 7-22. Septic systems damaged by scour and buoyancy

Figure 7-23. Damaged water line at Rollover Pass bridge crossing

Figure 7-24. Damaged storm drains (Rollover Pass, left photo; The Biscayne, right photo)

Figure 7-25. Damaged utility lines due to scour

Chapter 8: Marina Performance

The boating industry has a major presence in Galveston and adjacent bays. Slip space in marinas is rented at a premium and houses a wide variety of vessels from yachts to sailboats to small powerboats. The damage assessment team visited several marinas to determine the level of damage and which storm damage mitigation measures (if any) had worked.

The team visited the following marinas:

- Bolivar Yacht Basin
- Galveston Yacht Basin
- Seabrook Shipyard (Marina)
- Houston Yacht Club
- San Leon

A view of some of the effects of the storm surge plus wind is indicated by the boat in Figure 8-1.

Figure 8-1. Example of boats carried inland with storm surge

Bolivar Yacht Basin

The team also had the opportunity to visit the Bolivar Yacht Basin which is located on the back side of Bolivar Island. It had covered and uncovered boat slips of various sizes, several of which contained boat lifts. Covered and uncovered RV parking was also available. Metal roofing material was used to cover the slips. Figure 8-2 shows the damage that occurred to the roofing material at the edges where uplift was significant.

Figure 8-2. Damages to roof at Bolivar Yacht Basin

The marina received significant structural damage from the storm. There were several instances of appliances and other household materials that had been pushed into the boat slips (Figure 8-3). Some of the debris could have come from the damaged restaurant. Roof material was stripped off the covered boat slips in many instances and carried to the open area landward of the marina. Many of the taller slips still maintained their roofing material, albeit with edge damage from the wind (Figure 8-4).

Figure 8-3. Appliances in the water near boat slips

Figure 8-4. Damage to smaller slips

Not many boats were in slips during the team's site visit; it was not clear whether they were evacuated prior to the storm or were removed by the storm. There were several boats in slips with varying degrees of damage; the storm surge had washed others onto the land. A heavily damaged camper remained on the property.

Galveston Yacht Basin

The Galveston Yacht Basin is located east of the Port of Galveston on Galveston Island about 3 miles southwest of the center of the entrance to Galveston Bay on the bay side of the island and across the channel from Pelican Island. All piers in the basin are fixed. Some of the damages are a result of mooring lines putting too much stress on the vessels and the docks. A multitude of covered and uncovered slips accommodate various sizes and classes of boats. Boat slings are provided for use with motorized boats in the covered slips. Some pictures of Galveston Yacht Club are shown in Figures 8-5 and 8-6 to illustrate the pre-storm conditions. These were actually taken one year after Hurricane Ike when the marina was restored to pre-Ike conditions. In Figure 8-5 the wall on the right separates the marina from the adjacent arm of Galveston Bay. The wall was overtopped during the storm and some boats were said to have floated across the wall.

Most of the covered facilities appeared to have survived with minimal damage, though many of the boats in slips suffered varying degrees of damage. The Yacht Club provides smaller slips (for small trailerable vessels) equipped with boat slings to enable transport of the vessel in and out of the water. Many of these boats were left elevated in slings during the storm. Several boats in slings had either fallen in the water or twisted in their slings. Others had slipped their slings and ended up on the dock or in the water. The boat damage underscored the observation that boat slings are not suitable protection for vessels from hurricane damage. Figures 8-7 and 8-8 provide examples of damage in the small boat facilities.

Figure 8-5. Sailboats at Galveston Yacht Club, in conditions similar to pre-storm

Figure 8-6. Powerboats at Galveston Yacht Club, in condition similar to pre-storm

Figure 8-7. Boat twisted upside down in its sling in covered facility

Figure 8-8. Boat resting on dockside pile in covered facility

Larger, covered slips are provided for power yachts that are too large for standard boat trailers. These slips do not have slings. Damage levels varied, though these vessels seemed to fare better than the smaller powerboats in slings. Several of the larger power yachts appeared to have straddled piles, indicating that their leads may have been too long to ensure that the vessel settle back into the proper slip after rising with the surge. These boats do not appear to have been damaged by collision with the underside of the roof covering their slips. Figure 8-9 shows a power yacht straddling the piles.

The uncovered facilities used for sailboats appeared to have undergone moderate to severe damage. The water in this area was laden with storm debris, and there was evidence of piles being snapped in half in several slip locations. Several cleats had been pulled off the concrete deck; the connections were either undersized or connected too close to the edge of the concrete. Storm debris was present on the dockside nearest the bay. Damage to boats was widespread here; several had broken masts, and many had damage to the gunwales due to collision with or rubbing against the piles. There is some suspicion that several boats were not properly configured to survive a storm. Several boats had ripped sails and broken masts, and some slips only appeared to have one or two fenders. Figures 8-10 through 8-13 show examples of this damage.

Figure 8-9. Power yacht straddling piles, Galveston Boat Basin.

Figure 8-10. Damage to gunwales and masts, Galveston Yacht Club.

Figure 8-11. Storm debris quayside, Galveston Yacht Club

Figure 8-12. Broken column, Galveston Yacht Club

Figure 8-13. Storm debris in water, Galveston Yacht Club. Kajiro Suzuki, Ph.D., member of damage assessment team, is shown on the right.

Seabrook Shipyard

Seabrook Shipyard is located on the west side of Galveston Bay, inside Clear Lake Inlet, and near the city of Seabrook, Tex. Although it is named as a shipyard, it is really a full-service marina. Clear Lake is home to nearly 10,000 boats in wet slips and dry stack storage. There are many marinas and facilities providing boating services in this area.

The marina boasted a large covered floating dock structure, which would allow the dock to rise with the surge. This structure appeared to perform well, although some scarring of the piles was evident as the floating dock rose and fell while buffeted by the surge. There was also some damage to part of the floating marina's siding. Figure 8-14 shows the marina; the scarring of the piles is evident as the storm surge lifted the floating finger piers.

Another floating dock structure with a fixed roof at the facility did not perform as well. That structure suffered more damage as a tall vessel floated into the roof and buckled it (Figure 8-15).

At Seabrook Shipyard, as well, there was evidence of improperly secured vessels with lines that were either too long (allowing too much movement during the surge) or too short (breaking the moorings).

Figure 8-14. Covered floating dock, Seabrook Shipyard

Figure 8-15. Damage to boat and roof of floating dock, Seabrook Shipyard

Houston Yacht Club

The Houston Yacht Club is located further north, near Shoreacres, Tex., and in contrast to Seabrook Shipyard, is located directly on Galveston Bay. As mentioned, the facility was heavily damaged by Hurricane Alicia in 1983, and as a result, its staff had instituted a detailed disaster plan. This plan includes staged removal of boats—ranging from removing trailerable boats altogether to finding alternate dockage for cruising boats—beginning 72 hours before predicted landfall. The plan also calls for a buddy system to help in the event that a boat owner could not be reached to evacuate a vessel.

The damage to the marina and boats was significant. The yacht club's breakwater, which was made up of wooden slats, was overtopped by the waves and surge from Hurricane Ike. The bulkheads bordering the harbor were overtopped and backfill lost because there was no geotextile or filter material to prevent sediment loss between the sheathing boards. Several boats had broken loose from their moorings and were scattered around the yacht club. Some were forced further into the docks, while others ended up on the club's lawn. Others were flooded and submerged, perhaps due to shortened lines.

In other areas of the facility, there was significant pavement damage, as the surface separated from the sublayer in many instances. As with the other marinas, there was a large amount of debris floating in the water.

Figures 8-16 through 8-21 show damage from Hurricane Ike at Houston Yacht Club.

Figure 8-16. Boat driven through dock, Houston Yacht Club

Figure 8-17. Severe dock damage, Houston Yacht Club

Figure 8-18. Erosion damage behind harbor bulkheads, Houston Yacht Club

Figure 8-19. Boat and dock damage, Houston Yacht Club

Figure 8-20. Wooden crib breakwater filled with stone, Houston Yacht Club

Figure 8-21. Asphalt damage in parking lot, Houston Yacht Club

San Leon Fishing Harbor

The fishing harbor in San Leon, Tex., borders the west side of Galveston Bay. This harbor contained a fishing dock that was not in use during the team's visit.

As with the other marinas, several boats had broken loose of their moorings and washed into the bulkheads and piers. Damage here was relatively minor compared to that sustained at the Houston Yacht Club. An example of the damage is shown in Figure 8-22. The figure shows that the water level and waves overtopped the breakwater, directly affecting the infrastructure and vessels within the harbor.

Figure 8-22. Boat and bulkhead damage, San Leon Fishing Harbor

Damage from Previous Storms

The last major storm prior to Hurricane Ike to impact the area was Hurricane Alicia, which made landfall near Galveston as a Category 3 storm on August 18, 1983. Storm surges were estimated to be about 2.75 m on the gulf side of Galveston and about 3 to 3.65 m near Baytown (NHC 2002). As with Hurricane Ike, the effects of Hurricane Alicia were felt far from the actual point of landfall. For example, the surge from Hurricane Alicia, along with normal high tides, pushed water over the outer seawalls of Houston Yacht Club's outer harbor, eliminating any protection from the storm and either sinking or carrying ashore all 141 boats docked in the facility (Boat US 1999). As a result, a detailed hurricane preparedness plan was developed with a detailed staging plan that included the removal of all boats in the outer harbor. Damage reports in the wake of Alicia on other marinas in the area were not immediately available.

Summary

Damage to the area's marinas varied widely, with Galveston Boat Basin seemingly receiving modest infrastructural damage from the storm. It is also likely that exposure to high water levels and waves in Galveston Bay were responsible for the difference in damage between Seabrook Shipyard and the Houston Yacht Club. The floating dock, roof structure, and finger piers at Seabrook Shipyard appeared to work as designed, and its performance seemed to mitigate the level of damage that would otherwise have occurred.

However, it is clear that the improper securing or maintenance of boats to survive a storm contributes to facility damage. Boats that break free of their moorings or that still have masts and sails in place when a storm arrives can cause tremendous damage; they can collide with docks, bulkheads, other boats, and even buildings. While it is likely that broken piles and detached cleats (as seen at Galveston Yacht Basin) also contributed to boats becoming loose during the storm, much damage can be mitigated by properly securing vessels and providing an appropriate amount of fenders for them. Additionally, slinging small powerboats out of the water does not provide sufficient protection for them during a storm.

While the Houston Yacht Club had storm preparedness plans in place, it was not clear whether those plans worked, given the large amount of damage sustained by the facility. It was also unclear if other marinas had similar plans in place.

Chapter 9: Policy Issues

The Coastal Zone, in general, includes the land areas that are affected by the ocean and the ocean areas that are affected by the land. Coastal zone management is a process for the sustainable use, development and protection of these areas. In the United States, each coastal state is responsible for designation of the extent of the coastal zone, its management, and the development of appropriate laws and regulations for stewardship of the coastal zone. The Texas coastal program was established by the Coastal Coordination Act (Senate Bill 577, 65th Texas Legislature, Regular Session, 1977) and is implemented by a network of program agencies, coordinated through the Coastal Coordination Council. The Texas General Land Office has primary authority for the program. The Program's purpose is to ensure the long-term coastal economic and ecological productivity and to improve the management of the coastal natural resource areas. The Act provides policies for construction of various special facilities, such as energy and utilities, policies for water quality and dredging, and policies for construction in dunes, in hazard areas, within coastal barriers and in parks, wildlife management areas and preserves. One of the express goals of the Act is "to ensure and enhance planned public access to and enjoyment of the coastal zone in a manner that is compatible with private property rights and other uses of the coastal zone (Texas Administrative Code, Title 31, Part 16, Chapter 501.12)."

In addition to the Coastal Coordination Act, the Texas General Land Office is responsible for administration of the Texas Open Beaches Act (Natural Resources Code, Title 2, Subtitle E, Chapter 61: Use and Maintenance of Public Beaches). This law insures that the public has free and unrestricted access to state-owned beaches bordering the Gulf of Mexico, and in conjunction with the Dune Protection Program in the Coastal Coordination Act the law helps protect and preserve Texas beaches. The law, as adopted in 1959, covers those beaches that extend from the line of vegetation to the line of mean low tide. Both the Open Beaches Act and Dune Protection Program[1] are designed to:

1. Help beachfront property owners and local governments maintain a healthy beach/dune system
2. Assist local governments in managing the Texas coast so that the interests of both the public and private landowners are protected
3. Reduce the erosion of public beaches and discourage erosion-response methods such as rigid shorefront structures that can have a harmful impact on the environment and public and private property
4. Reduce flood losses and minimize loss of life and property
5. Protect the public's right of access to, use of, and enjoyment of the public beach
6. Ensure timely and predictable governmental decision-making and permitting processes
7. Educate the public about coastal issues.

The line of vegetation, along with being the inland extent of the Open Beaches, has been used to determine the seaward limit of development or a development setback, both for protection of the public beach area and to reduce flood losses and to minimize loss of life and property. However, the line of vegetation does not represent a fixed or permanent boundary line; along an active coast the line of vegetation can move and on an eroding coastline, movement of the line is generally

[1] (Texas General Land Office Website; http://www.glo.state.tx.us/coastal/beachdune.html; last consulted 2 January 2010)

inland. This moves the boundary for "safe" or minimal loss area inland and the area of public beach access inland.

As noted in the earlier discussion on coastal processes and shoreline change, erosion along the upper Texas coast is variable. Ranges of erosion or accretion are available for reaches of the coast, but they do not represent conditions at individual locations. Some areas are receding more rapidly than average and others are advancing. In addition to the local variability of shoreline change, the changes from episodic events like Hurricane Ike can cause extensive changes in the shoreline that differ greatly from the short-term historic shoreline trends. Despite the difficulties in determining location-specific shoreline change rates for either long-term or episodic conditions, information on shoreline change is important for decisions on development in close proximity to beaches.

Public Education of Coastal Hazards

Development within the coastal zone should be governed by appropriate regulations, and individual decisions to reside or work in this zone should be made with the full understanding of the associated hazards and risks. Agencies in the Coastal Coordination Council need to provide information on shoreline change that can help provide for both the continued availability of beach access for public use and for the safe use of inland zones for development. Developers and property owners also have responsibility for investigating coastal hazards and keeping track of current information, such as background rates of erosion, benefits of elevating buildings to or above the FEMA minimum requirements, additional hazards due to proximity to the shorelines, especially in eroding areas, and the current knowledge of global climate change with the possibilities of future increase in sea level rise and storminess, and such. The more fully the prospective builder/homeowner is educated in general and informed of the risks, the better.

The General Land Office has embraced beach nourishment to expand the area of public beach access and provide greater protection for back beach development. These efforts also require information on coastal change to identify opportunities for sustainable nourishment efforts. A main driver in the decision to maintain nourished shorelines is awareness of the natural and man-made forces that must be addressed during beach maintenance. Generally this equates to the rates of historic erosion. The extensive damage due to an event such as Hurricane Ike both reveals the risks and need for comprehensive and long-range policies and places the issues in perspective for fresh analysis. Policies are needed for response to storms and erosion that encompass both private and public facilities and the protection of both private and public concerns.

Prior to Hurricane Ike, more than 100 private residences were located in the Open Beach area, due to the landward movement of the vegetation line. Hurricane Ike moved the vegetation line tens of meters landward along much of the upper Texas coast. Hundreds more home site (lots that no longer contain a habitable structure) are now seaward of the vegetation line. These homes and destroyed home sites hinder access to the public beach area and create a hazardous situation for beach users. They also represent a major test for the Open Beaches Act. Immediately after the hurricane, the Texas Land Office set a 120-day moratorium on building to see whether the vegetation line would accrete from its hurricane-related position. During this period, the General Land Office worked to develop a policy for rebuilding that would be fair to both the private property owners and the public using the beach. An interim development line was set as the area inland of the 4.5-foot contour. More recently, the open beach area has been set as being 200 feet inland of mean low water and the development line is based upon both the open beach area and setback from the vegetated dune.

Chapter 10: Lessons Learned

Many of the lessons learned from Hurricane Ike are the same as previous hurricanes.

- Erosion is an important determinant of coastal hazards and contributes to increasing vulnerability of upland structures with time. Shoreline erosion rates and the long-term consequences of erosion need to be communicated to the public in general and property owners in particular.
- Storm-induced scour, both shoreline retreat and localized scour around structures, can contribute to structural failure due to compromised foundation stability. Local structure-induced scour depends on several local factors, and the cause and effect relationships are a function of location conditions.
- The key components for successful storm-resistant coastal buildings include open, elevated foundations, adequately imbedded to tolerate a combination long-term erosion, storm-induced erosion, and localized scour throughout its useful lifetime; sufficient elevation of the living area that the lowest horizontal foundation members never get hit by a wave; and good wind-resistant construction. The safety factors over minimum standards are deeper piling embedment, higher floor elevations, uniformly improved wind connections throughout the building, and a more water-penetration-resistant building envelope.
- Hurricane Ike transported large volumes of sand from the beach to inland areas, forming extensive overwash fans 100 to 150 m inland of the shoreline. Finding debris lines further inland than the overwash fans suggests that sand volume was a limiting factor to the extent of the overwash fans.
- The Galveston Seawall and the increased elevation landward of the seawall (grade raising) effectively protected the inland development from major water-related damage.
- The geotube installations had observable but limited benefits for the surge and waves from Hurricane Ike. This is likely due to the surge overtopping the tubes.

Lessons learned from field observations

The erosion rate is an important determinant of coastal hazard contributing to the increase in vulnerability of upland structures with time. Erosion rates should be communicated to the broad public with emphasis on approaches to shoreline stability and their applicability to the shorelines of interest. Consideration should be given to disclosure of shoreline change rates as a requirement in deed transfers.

Storm-induced scour includes scour due to shoreline retreat and local structure-induced scour. Both can contribute to structural failure due to loss of piling embedment. Scour due to shoreline retreat is statistically predictable, and models exist for the prediction of scour due to individual storm events given the storm surge and wave time series. Local structure induced scour depends on several local factors and interactions with localized wave effects. These relationships are still poorly understood, and structure-induced scour cannot currently be predicted or modeled. Future field reconnaissance studies should include more comprehensive documentation of local scour characteristics with a focus on depths, horizontal dimensions, orientation to the likely flow direction, and soil and structural characteristics, such as scour around piles, base of geotubes, edges of pavement, and concrete pads. Pre- and post-Ike LIDAR surveys should be analyzed to extract as much of these data as possible.

The Galveston Seawall and the raising of portions of Galveston Island through filling after the 1900 Galveston Hurricane were effective in eliminating water-related damage to the structures protected by these improvements. The seawall design protected the inland development from wave forces and surge; however, some water-borne debris was carried onto the road immediately inland of the seawall.

The extensive geotextile installations constructed along Galveston Island and portions of Bolivar Peninsula have proven to be effective in reducing shoreline retreat and damage to upland structures from lesser storms; however, the benefits appeared to be limited for storms of the magnitude of Hurricane Ike, possibly because of submergence by the surge and storm tides. Along much of the survey area, the waves and surge from Hurricane Ike exceeded the protective capacity of the geotextile tubes, and inland areas were observed to have experienced significant water-related damage. Some development landward of intact geotextile tubes fared slightly better than development without any protection. The tubes may have created a breakpoint, causing a damping of the wave energy and providing a level of protection not found on the adjacent beaches. In areas where the tubes remained filled, scour occurred on the oceanfront side of the tubes and ran parallel landward of them.

Each major coastal event provides lessons to be learned that can help the affected community in its recovery process, provide valuable data and insight to engineers and planners who are working in the field, and provide direction for government agencies and decision-makers on opportunities to reduce the recurrence of preventable problems. Often a lesson is repeated from several locations or has been identified from prior disasters at the same location. The improvements that come from the study of each disaster become an incremental learning process, with opportunities available in the aftermath of each event. It is important to document damage from major events and provide lessons learned. With each report, more projects will learn from prior lessons, and there will be fewer avoidable problems and less storm damage.

Lessons Learned from Prior Events

During the Hurricane Ike field investigation in Galveston, there was much discussion of the 1900 storm that was the impetus for elevating the eastern part of the island and building the initial Galveston Seawall. In October 1900, W.J. McGee prepared a report, *The Lessons of Galveston.* McGee's lessons, in summary, were:

1. Do not build a house on sand; "the strata are loose sands and silts and mud beds, nowhere firm enough to afford a sure foundation. … no worse coast-stretch for foundations exits (sic) in the world." (McGee 1900, 378)

2. "It is the business of the engineer and architect to look to foundations, and to avoid the traditional house on sand; but it is the duty of the nature student to interpret natural records and guard against the building of houses within reach of storm waves." (McGee 1900, 379)

3. Coastal subsidence, up to 1 foot every 20 years between Mobile Bay and Galveston Harbor, forms and influences the Gulf Coast. And, "of all locations on the Gulf coast, Galveston is most exposed; it is the last of the great natural embankments of the west coast remaining unsubmerged, and hence it opens to a wider range of gales than any other." (McGee 1900, 382)

4. The 1900 Storm showed that disaster in Galveston was a national and even international tragedy and people from around the world sent sympathy and aid.

These lessons were again observed during field investigations on Hurricane Ike. There were examples of building foundations that failed due to insufficient pile depth; existing homes had been located in the surf zone or wave overwash zone. The tide record has shown that Galveston has continued to experience subsidence, measured as a high relative rate of sea-level rise. Finally as in 1900, the disaster in the Galveston area was felt around the United States and overseas.

Need for Comprehensive Evaluation of Regional Vulnerability

Most of the areas of damage were not individual locations affected by a single factor, but regional is scope and resulting for multiple conditions—some scour, some wind, some waves, some inadequate design, construction or additions, some poorly planned development, and/or some inadequate maintenance. Few damage sites could be attributed to one single cause. The placement of shore protective structures, roads, drainage channels, sewer pipes, water lines, paved areas, and landscaping can all influence the potential storm damage exposure of an individual site. Actions taken for individual projects can and often do influence locations other than the main project site. An obvious example for Galveston is the construction of the seawall, the erosion and storm wave protection provided to inland sites, and the erosion and storm wave exposure that develop at the areas downcoast of the seawall.

Large portions of Galveston were elevated in conjunction with the seawall construction. Several newer developments include a combination of created water features with the excavated material used to provide elevated building areas. Some roads are elevated above existing grade. These modifications to land form will alter local drainage, and some can alter area or regional drainage patterns. Seawalls that are designed to keep water out of an area can also prevent water from leaving an area once it gets passed the barrier; roads designed to keep the road surface safe during times of high water can redirect water to other locations. Site drainage is a normal consideration for projects of any size, but in islands or areas with multiple directions of exposure, drainage beyond the project site can be a significant concern. As seen in some of the flooding in New Orleans after Hurricane Katrina, flooding protection that surrounds an area has the potential to pond water or create a "fishbowl." Flooding occurred landward of the Galveston Seawall in what appeared to be a similar situation. Exposure to flooding (including runoff and bayside inundation) and drainage patterns for this area might need to be reconsidered relative to currently existing development patterns for the entire area.

Erosion and flooding are two of the possible hazards that can be modified by off-site development. These examples point to the need for comprehensive planning and examination of hazard exposure and vulnerabilities at a regional scale. Individual projects would then need to be examined and analyzed within the context of the regional hazards. A general engineering tenet and community planning goal is to avoid harm to the proposed development and the surrounding area. The National Environmental Policy Act requires analysis of cumulative impacts of those new projects that undergo this federal review. The focus on a comprehensive examination of hazards is often more a goal than a reality. While it is normally best to undertake comprehensive hazard planning before a hazard event, the impetus for such planning often happens only after an event. A change in this approach may not occur overnight, but, at a minimum, each new hazard event should be examined for information on hazard exposure and vulnerabilities.

Post-storm debris was widespread. Debris was generated both at the local level (location in proximity to the source) and at the global level (debris dispersed from the source by incoming or outgoing storm tides). Post-storm cleanup occurs at the local and regional level and should be considered in any pre-hazard planning effort. Waste and rubble can block traffic routes and impede efforts to repair infrastructure and damaged building; the volume debris removal is often far larger than routine waste management. Weeks or months of manpower, trucks, and construction equipment may be needed for community clean-up; diverting these resources away from repairing and restoring community infrastructure. A community's ability to recover is in part a function of the time it takes to remove the debris.

Erosion is an important indicator of coastal hazards and contributions to increasing vulnerability of upland structures with time. Shoreline erosion rates and the long-term consequences of erosion need to be communicated to the public in general and property owners in particular.

Storm induced scour, both shoreline retreat and localized scour around structures, can contribute to structural failure due to compromised foundation stability. Local structure-induced scour depends on several local factors and the cause and effect relationships are specific to the local conditions. Focused engineering studies on these failures could inform either best practices or official building codes in these high hazard areas.

Hurricane Ike transported large volumes of sand from the beach to inland areas, forming extensive overwash fans 100 to 150 m inland of the shoreline. Debris lines more inland than the overwash fans suggest that sand volume was a limiting factor to the extent of the overwash fans. Sand management policies should be in place prior to these events so that individuals and communities have guidance on best practices for post storm cleanup, debris removal, and sand redistribution.

Adequacy of Current Regulations

A single disaster event will rarely result in radical changes to the basic engineering and planning approached to coastal hazards. The 1900 Galveston storm did generate change. Most coastal disasters and the surveys of these disasters add incrementally to hazards awareness, providing new details on high water marks that can be used for planning and to calibrate surge models, documenting the performance of various shoreline structures, building techniques and designs, and documenting some of the large-scale changes to the coast that may or may not establish new baselines for coastal change. Not every field survey finds some new or unexpected results; the field investigation of Hurricane Ike was one of these. It did provide information that will improve the understanding of coastal hazards. Hurricane Ike caused enormous damage to the Galveston region, loss of life, and long-term disruptions to the lives and businesses of people in its path. It is hoped that the ASCE field survey and other investigations can provide measurements and observations that will influence recovery efforts so that damages will be minimized when the next hurricane occurs.

Appendix: Storm Hydrographs at Area NOAA Stations

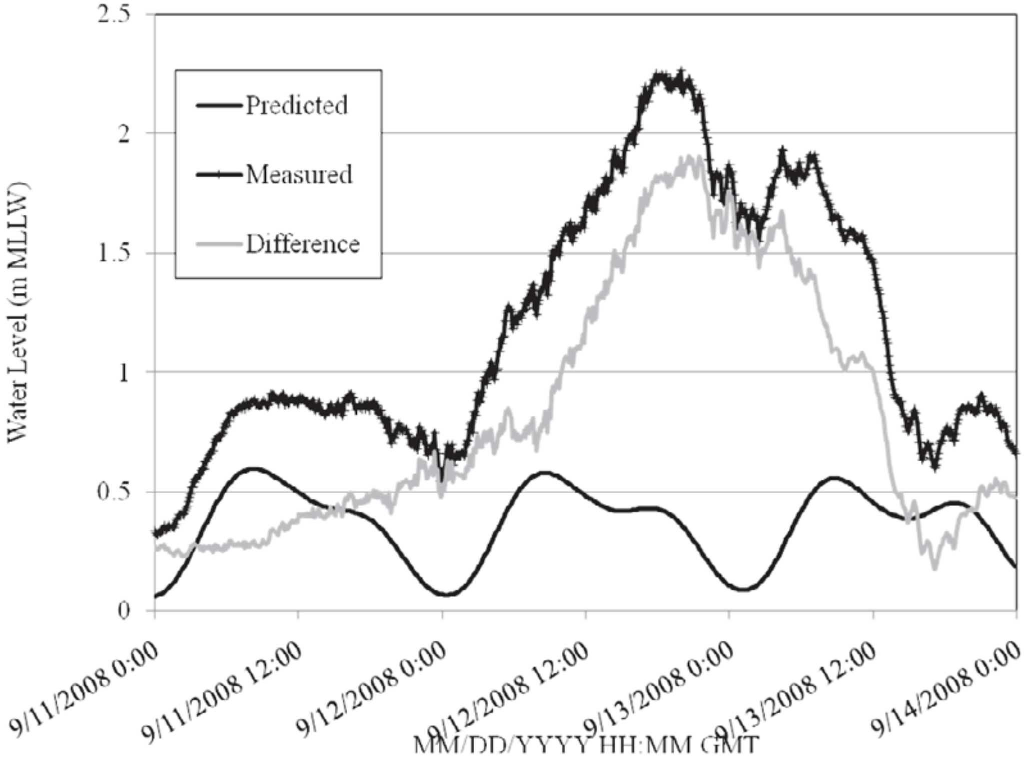

Figure A-1. Measured and predicted water levels at Freeport, Tex.

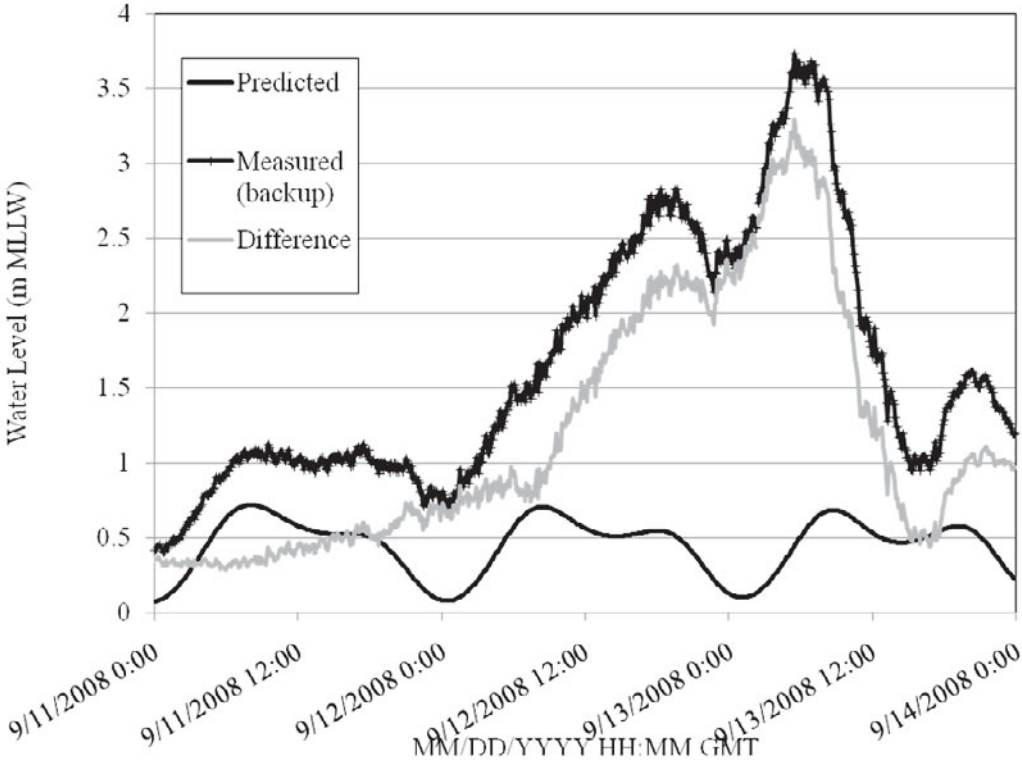

Figure A-2. Measured and predicted water levels at Pleasure Pier, Tex.

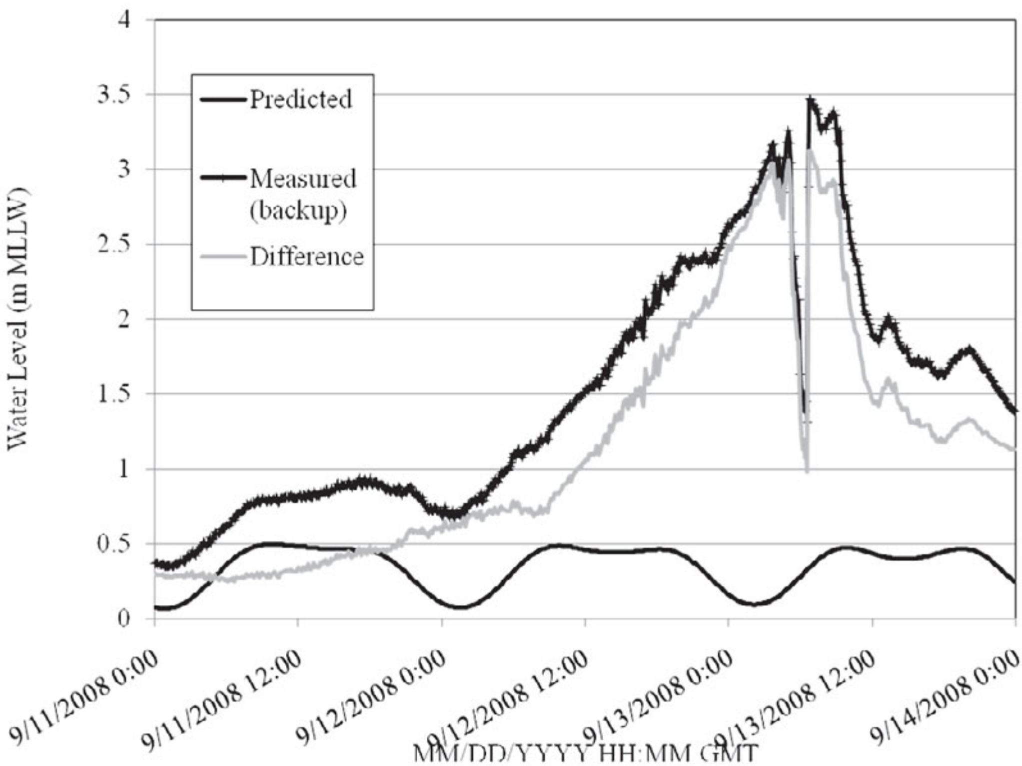

Figure A-3. Measured and predicted water levels at Pier 21, Tex.

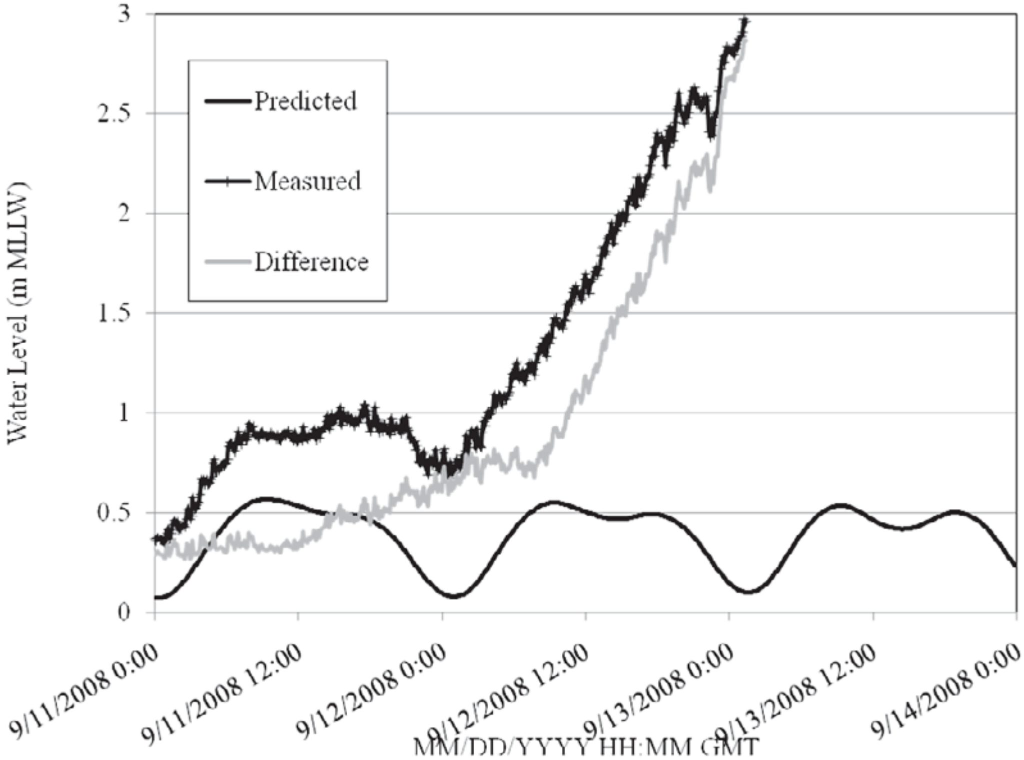

Figure A-4. Measured and predicted water levels at Galveston Entrance, Tex.

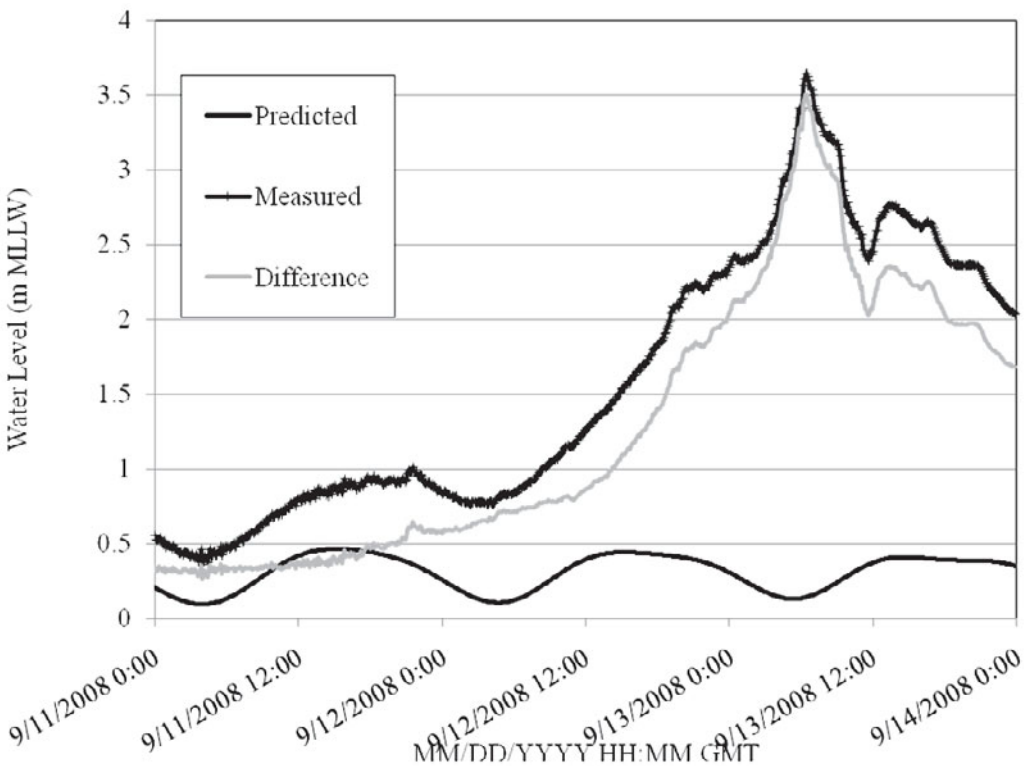

Figure A-5. Measured and predicted water levels at Eagle Point, Tex.

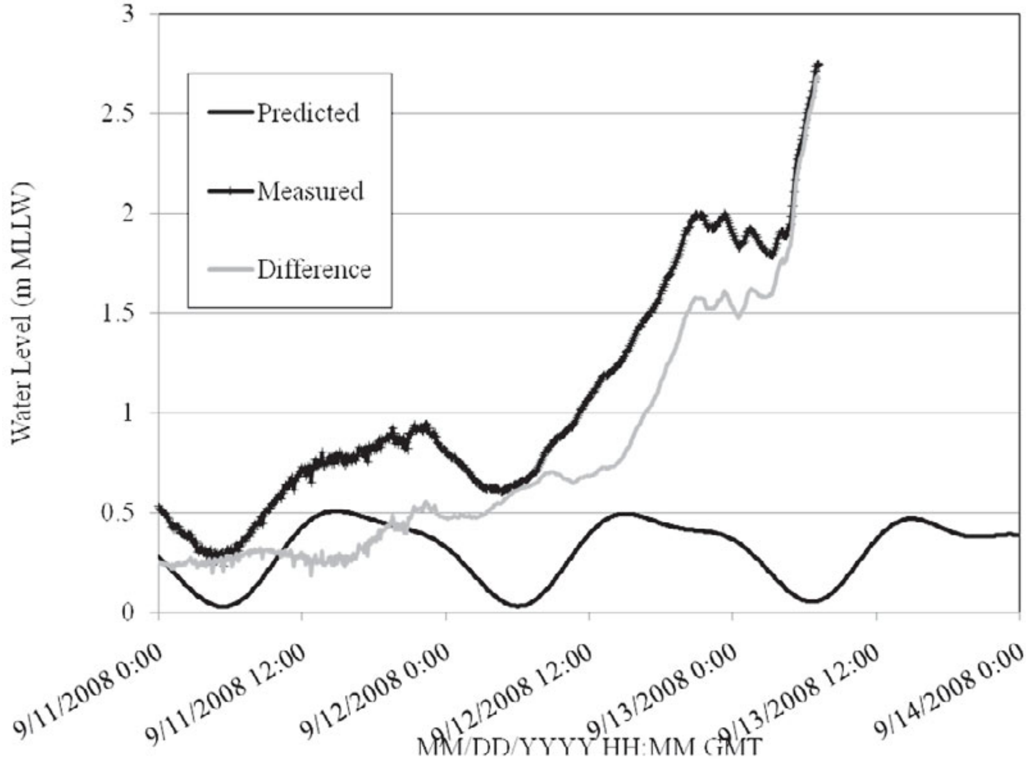

Figure A-6. Measured and predicted water levels at Morgans Point, Tex.

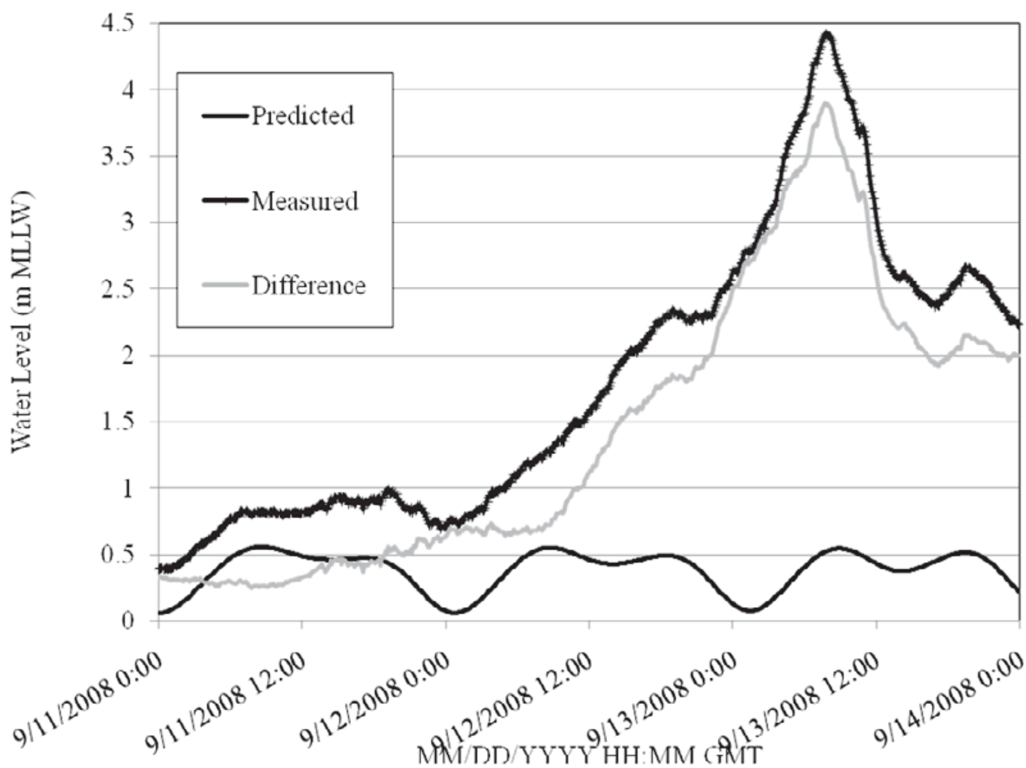

Figure A-7. Measured and predicted water levels at Sabine Pass, Tex.

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