CHAPTER SEVENTEEN

HURRICANE SURGE PROTOTYPE DATA COLLECTION

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INTRODUCTION

Storm surges from hurricanes have even more devastating effects on human lives and property than the high wind velocities associated with such storms. Storm surge forecasts are necessary as a guide for emergency action to prevent disasters due to coastal flooding caused by tropical storms. The design and evaluation of coastal structures are also dependent on estimates of storm surge levels. Several numerical models have been developed that appear to reasonably predict the surge from storms of given size and intensity, but they sometimes differ significantly among themselves. A comprehensive data set is needed to quantitatively evaluate these models. These data will also provide a better understanding of coastal processes during periods of severe wave activity and high water levels, and will better define coastal and inland water elevation time histories, high water marks, and water velocity fields caused by tropical storms and hurricanes.

The U. S. Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), under the sponsorship of the Office Chief of Engineers (OCE), has been involved for several years in a project entitled Hurricane Surge Prototype Data Collection Work Unit, the primary objective of which is to collect such a data set. In addition to the work being performed by CERC personnel, a cooperative program has been established with the Nuclear Regulatory Commission (NRC) and the University of Florida to collect surge data along the coast of Florida. A cooperative program has also been established with the National Ocean Service (NOS) to "harden" tide stations in the Gulf of Mexico and along the Atlantic Coast of Florida to survive hurricane forces and record the full range of anticipated surge levels.

This paper describes CERC's long term, ongoing Hurricane Surge Prototype Data Collection project, as well as the data collected.

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SURGE CHARACTERISTICS

The most destructive element of a hurricane is the storm surge. Simpson and Riehl (3) define it as "a shoal water process generated by hurricanes resulting in a superelevation due to a combination of direct wind driven water and an uplift induced by the pressure drop; together they reach maximum heights as the hurricane center arrives at an ocean or bay shore". In addition to the wind and pressure induced rise in water level, astronomical, secular and seasonal tides, freshwater runoff from heavy rains, and the outfalls from rivers and streams all have a hand in the creation of a massive still water platform. This platform can reach far inland to places that ordinarily would remain quite safe and dry.

The hurricane storm surge height, H_s, is a function of three principal sources of setup (Simpson and Riehl, 3):

$$H_s = f(S_b, S_w, S_v)$$

where,

S_b = setup due to the dynamic inverse-barometer effect, and is concentric to the low pressure center

S_w = setup due to the stresses from the irrotational component of the wind

S_v = setup due to the stresses from the rotational component of the wind

S_w is the major component of the surge in more protected areas, such as basins, bays, or estuaries; whereas, S_v is the major component of storm surge along the open coast.

When a hurricane reaches landfall at an open coast, its peak surge height will be larger with lower central pressures; with an increase in the radius of maximum winds up to 30 miles (48 km); with increased speed of coastal approach; and with a decreasing slope of the bottom surface from the beach seaward for a distance equal to the diameter of the maximum winds (1,3). Storm surges in bays and estuaries may be larger than those at an open coast by 50% or more for slow moving storms.

HURRICANE SURGE DATA COLLECTION

The approach selected to provide a high quality, comprehensive data set was to develop rapidly deployable instrument packages that could be installed at preselected sites 24 to 48 hours before predicted landfall of a hurricane or tropical storm. To provide a sufficient quantity and quality of data, site surveys were undertaken approximately every 10 miles (16 km) along the entire Gulf Coast and the Atlantic Coast of Florida to select onshore locations for instrument deployment. More closely spaced sites were selected to provide a better picture of the time histories of hurricane induced water levels in major bays and estuaries in the project area.

Selection criteria for the onshore sites were as follows:

a. Smooth, flat terrain where possible, to minimize small scale effects on the storm surge measurements.

b. Absence, or a minimal number, of man made or natural structures near the site that could influence propagation of surge, but would not be represented in numerical surge models.

c. The existence of a structure on which to mount instrument packages that had a high probability of surviving a major hurricane.

Obviously, not many sites could meet the criteria exactly. The site selection process required numerous compromises in selecting locations that would both provide quality data and withstand the rigors of a severe storm. At this time, 265 sites have been selected and catalogued in Texas, Louisiana, Mississippi, Alabama, and Florida. These locations are depicted in Figure 1.

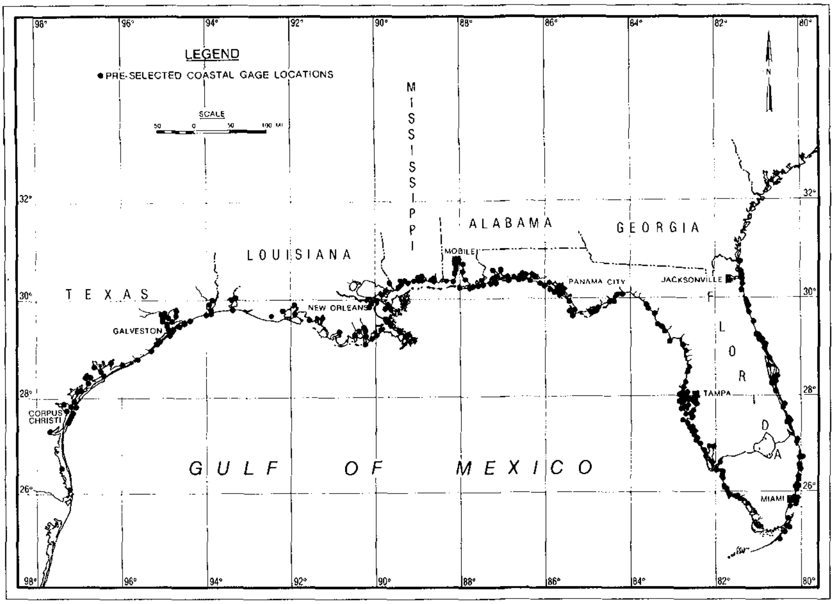

Figure 1. Preselected sites for onshore surge gages.

When a hurricane or tropical storm threatens the coast and the area most likely to be inundated is identified, water level instruments and mounting hardware necessary to occupy the preselected sites are loaded aboard a specially equipped deployment vehicle and the field team proceeds to that area. The final decision on which preselected sites to occupy is made as more specific information on the expected point of landfall becomes available from the National Weather Service (NWS).

As soon as possible after landfall, the CERC field team recovers all instruments and surveys the area to delineate points of maximum inundation and the areal extent of hurricane induced flooding. The elevation of each instrument is marked and later tied into the National Geodetic Vertical Datum (NGVD) during post storm high water mark surveys.

In coastal areas without substantial structures on which to mount the instruments (e.g. south Louisiana), instrument packages are operated continuously throughout each hurricane season on available offshore structures. Three instruments are currently maintained on Shell Oil Company Platforms. These offshore sites are particularly useful since they provide surge data with virtually no small scale local effects from the coastal terrain, so that the data can be used in establishing boundary conditions in offshore areas. All three offshore sites are shown in Figure 2 as WES instruments.

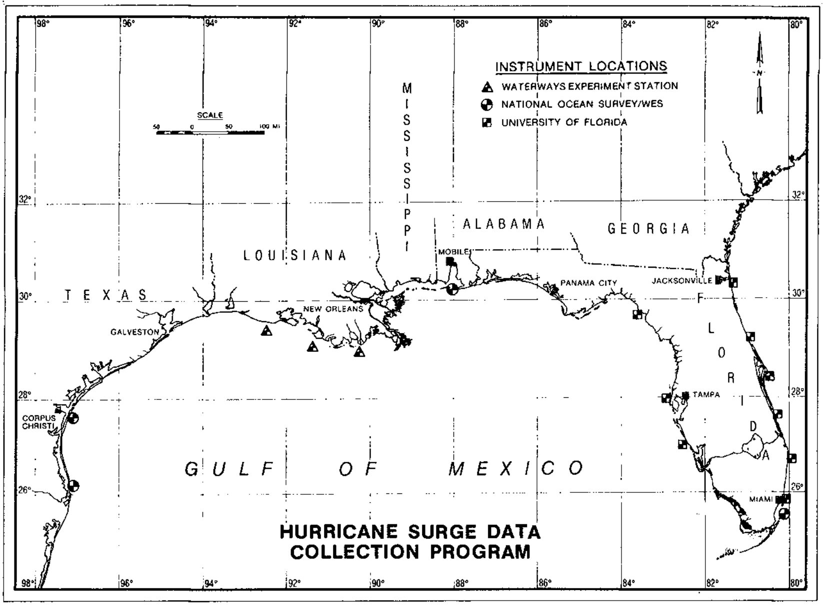

Figure 2. Permanent offshore surge gage sites.

Those instruments shown in Figure 2 as National Ocean Survey/WES sites are maintained as part of a cooperative effort with NOS. The sites in Miami, Dauphin Island, Alabama and Corpus Christi, Texas are NOS primary tide stations that have been "hardened" to survive hurricane conditions and contain a dedicated surge gage in addition to a standard float-well type tide gage. The fourth NOS/WES instrument in Cameron County near the southern end of Padre Island was installed specifically for hurricane surge measurements. The nine University of Florida sites on the Atlantic and Gulf coasts of Florida are wave and surge gages maintained as part of a cooperative effort with the Nuclear Regulatory Commission and the University of Florida.

INSTRUMENTATION

In order to quickly deploy large numbers of instruments prior to landfall of a threatening hurricane, the instrument packages needed to be compact, rugged, and easily deployable by a 2-man team in a conventional size truck. Other desirable factors were: an independent power supply for continuous data collection throughout the storm, and digital recording capability to interface with existing data processing systems.

Twenty internally recording pressure sensors were acquired for this purpose. These instruments are microprocessor controlled data loggers which use a strain gage sensor to measure pressure at selectable time intervals and record data on small, continuous loop tape wafers. The submersible instruments can be quickly clamped to a bridge or pier pile.

For the sites at which a water level gage is maintained throughout each hurricane season, it was necessary to acquire instruments that could operate unattended for long periods and still collect data at short time intervals. Digitally recording wave and tide gages were selected to meet this requirement and to fulfill an additional objective, collection of wind generated wave data during a hurricane or tropical storm. These instruments sense pressure with a quartz crystal transducer and record both instantaneous wave heights and time integrated tide heights on four track data cassettes.

The hardened surge gages maintained by WES and NOS employ a gas purged pressure gage to measure surge due to tropical storms or hurricanes. Gas purged pressure gages, commonly known as bubbler gages, use a compressed dry gas, usually nitrogen, to activate a pressure sensitive diaphragm. Changes in water level are detected through an open-ended gas filled tube and recorded on a clock driven strip chart.

CORRECTION OF ABSOLUTE PRESSURE TIDE RECORDERS

Use of uncompensated pressure measuring sensors such as those employed at the preselected sites requires the data to be compensated for changes in atmospheric pressure during passage of the storm. A change of 1 mb in atmospheric pressure is approximately equivalent to a change of 1 cm in water level. Changes in atmospheric pressure of 50 mb are common during passage of a storm, consequently, it is essential such changes be taken into account when computing a hydrograph from uncompensated pressure data.

The simplest and most accurate means of compensating the pressure record would be to place a barograph near the tide gage; however, this is seldom feasible both from logistic and economic standpoints. An alternative method is via an analytic model to interpolate in time and space using data observed elsewhere in the affected area. There are a number of models to choose from, some developed from theoretical considerations, others by empirical best fit to the smoothed pressure profiles of several hurricanes.

The model found to give the best fit to the observed data for previous hurricanes is:

$$\frac{P - P_o}{P_\infty - P_o} = C \text{ (Arctangent } r/R)$$

where

P - pressure to be computed

P_o - central pressure of storm

P_∞ - far field pressure

R - radius to maximum winds

r - distance from storm center at which pressure is to be computed

C - constant

RESULTS

Since the Hurricane Surge Data Collection program was initiated in 1980, Hurricane Alicia (August 1983) gave the CERC field team its first opportunity to use the technique described under actual hurricane conditions. Alicia was the first storm of the 1983 hurricane season and the first to make landfall in the continental U. S. since Allen in August 1980. Hurricane Alicia was unusual in that it developed in the central Gulf of Mexico and made landfall less than 2 days after showing signs of becoming a significant storm. Alicia was classed as a minimal category 3 at landfall on the SAFFIR/SIMPSON scale, which ranges from one to five.

Alicia was declared a hurricane at 0000 GMT 17 August 1983 with a central pressure of 991 mb and maximum sustained winds of 75 mph (120 kmph). The hurricane continued to intensify until it made landfall at the western tip of Galveston Island, Texas at approximately 0700 GMT 18 August. Its central pressure at that time was 963 mb with maximum sustained winds close to 115 mph (185 kmph).

The staff of CERC had been closely monitoring Alicia's development, when it became evident at 1700 GMT on 16 August that the storm was rapidly deepening, the field team was sent to the Houston-Galveston area, arriving at daybreak on 17 August. Galveston Island by this time was being evacuated. Since coastal water levels had already risen and the sea state was high, it was not possible to deploy onshore gages along the gulf side of Galveston Island and lower Galveston Bay. Information from the National Hurricane Center at the time indicated the storm would make landfall between Corpus Christi and Freeport, Texas. The field team thus departed from the Houston-Galveston vicinity for the Matagorda Bay area. Enroute, the team deployed one gage package at Baytown, Texas near the head of Galveston Bay, in the event that Alicia turned northward as it later did.

In the time remaining before landfall, the field team deployed gage packages at Port Lavaca and Palacios, Texas in the Matagorda Bay area. At 0300 GMT, 18 August, approximately four hours before landfall, the field team retreated to Houston to wait out the storm.

Hurricane Alicia made landfall at the western tip of Galveston Island, traveled northward and was classified as a tropical depression after moving past Houston at 0600 GMT 19 August.

After the passage of the storm, the field team returned to the Galveston area to recover the instrument packages and begin a survey of high water marks.

The final compiled data set was obtained from a variety of sources including gage records from the Corps of Engineers, National Ocean Service, and private corporations.

The data set contains:

a. Maximum water elevations from post-storm high water mark surveys.

b. Histories of the time averaged water level at both coastal and inland locations.

c. Areal extent of inundation.

Table 1 lists the gage location, responsible agency or institution for data, maximum water elevation, time and date, and reference datum. Figure 3 shows the locations of instruments that recorded water level data in the Galveston Bay area during hurricane Alicia.

Hydrographs at the Pleasure Pier and Pier 21 in Galveston (Figures 4 and 5) show the peak of the surge coincided with the predicted high tide. Assuming the tide and surge effects were linearly superimposed, the surge relative to the predicted tide was about 7.4 ft (2.25 m) at the Pleasure Pier on the ocean side and 4.9 ft (1.5 m) at Pier 21 on the bay side of Galveston Island. At Freeport, Texas, there were three peaks, two on 17 August, one day prior to landfall and one approximately coinciding with landfall. The three peaks were about 2.9 ft (0.88 m), 3.1 ft (0.94 m), and 2.5 ft (0.76 m) relative to the predicted tide. The highest surge value did not occur at landfall because Freeport was on the "backside" of the storm, i.e., the winds at Freeport were primarily offshore at the time.

As shown in Figure 3, the Pier 21 and Pleasure Pier gages are located quite close to one another and the hydrographs reflect this. The Hanna Reef gage, located on the opposite side of the bay, shows a

Table 1

Location	Agency	Maximum Elevation ft (m)	Time CDT	Datum
Freeport, TX	NOS	4.0 (1.22)	0630/17/08/83	NGVD
Pleasure Pier, Galveston, TX	NOS	9.0 (2.74)	0130/18/08/83	NGVD
Pier 21, Galveston, TX	NOS	5.8 (1.77)	0200/18/08/83	NGVD
Fort Point, Galveston, TX	CE	6.2 (1.86)	0200/18/08/83	NGVD
Seabrook, TX[1]	CE	8.5 (2.59)	0430/18/08/83	NGVD
T-14, Baytown, TX	CE	6.1[2] (1.86)	0245/18/08/83	NGVD
Baytown Refinery, TX	EXXON Corporation	10.2 (3.11)	0730/18/08/83	MSL
Anahuac, TX[2]	Texas State Water Resources Board	8.0[2] (2.44)	0800/18/08/83	NGVD
Hanna Reef, TX[1]	CE	6.0 (1.83)	0400/18/08/83	NGVD
Sabine Lake, TX[1]	CE	4.1 (1.25)	1400/17/08/83	NGVD
Calcasieu Pass, LA	CE	4.0 (1.22)	1600/17/08/83	NGVD

NOS - National Ocean Service
CE - Corps of Engineers

1. Time of peak surge estimated.
2. Incomplete hydrograph, see text.

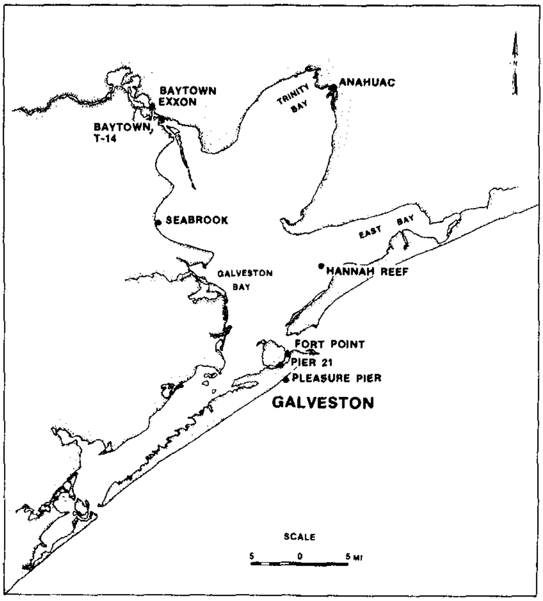

Figure 3. Tide gages operating in the Galveston Bay area during hurricane Alicia.

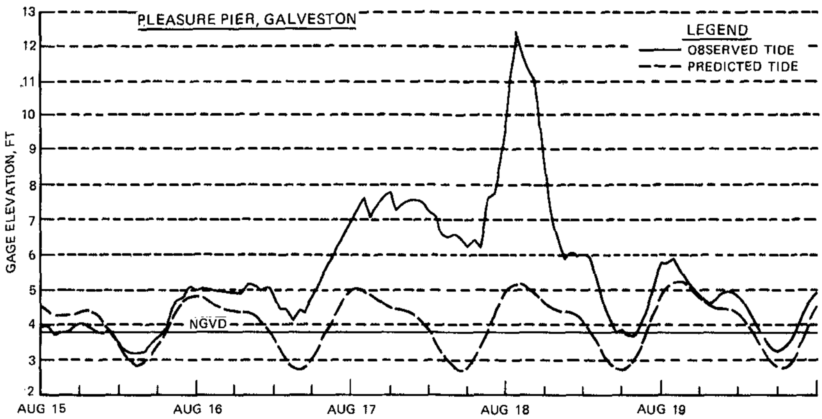

Figure 4. Hydrograph from NOS tide gage at the Pleasure Pier in Galveston.

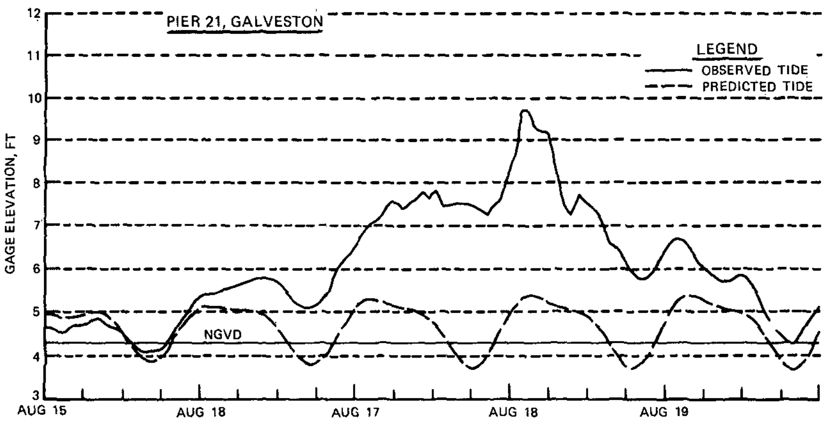

Figure 5. Hydrograph from NOS tide gage at Pier 21 inside the entrance to Galveston Bay.

broader peak followed by a relatively long tail. The broader peak and slower fall in water level were probably caused by waters that had been blown into the northwest reaches of the bay by the predominantly southeast winds during the storm flowing back into the Hanna Reef area after the storm had passed.

The gage at Anahuac recorded until submerged; attempts were made to determine a high water elevation nearby but the adjacent land is flat and featureless and overgrown with scrub vegetation.

The data obtained at the EXXON Corporation Baytown Refinery are a combination of readings from a strip chart recorder and digital readout. The strip chart recorder had a maximum excursion corresponding to about eight ft elevation. The water level sensor continued to function normally driving a remote readout from which surge heights were logged manually. The maximum surge recorded at the Baytown Refinery agrees very closely with nearby high water marks.

The CERC field team deployed two surge packages in Matagorda Bay, one at Port Lavaca and one at Palacios, Texas. Data from these gages showed no significant departure from the expected tide during passage of the storm. This is not unexpected as these gages were on the "backside" of the storm about 70 miles (112 km) from the point of closest approach.

The CERC gage T-14 functioned until about 0300 CDT 18 August when it failed. The cause of the failure was determined to be a defective pressure case which allowed water into the electronic circuits.

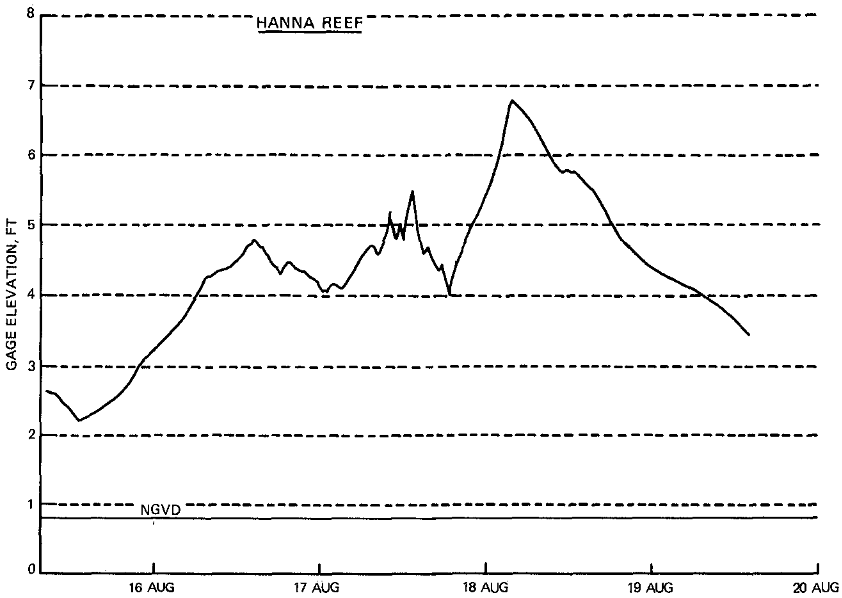

Figure 6. Hydrograph from tide gage at Hanna Reef in Galveston Bay.

POSTSTORM SURVEY OF HIGH WATER LEVELS

A poststorm visual survey of high water marks was made from Matagorda Bay east to High Island, Texas, including the shoreline of Galveston Bay, during the period 21-23 August 1983. The westernmost extent of surge induced flooding appeared to have been in the vicinity of Sargent, Texas at the eastern end of Matagorda Bay. Coastal flooding in this area, due to storm surge and wave setup, overtopped the low berm on the beach and built numerous washover fans on vegetated wetlands between the beach and a high man-made dune along the Intracoastal Waterway. The surge generated component of this rise in water level appeared not to exceed +3 ft (0.9 m) NGVD. Debris lines along the banks of the Intracoastal Waterway indicated a rise in water level of approximately +2 ft (0.6 m) NGVD.

At the U. S. Coast Guard Station in Freeport near the mouth of the Old Brazos River, high water overtopped a low bulkhead approximately 3 ft (0.9 m) above the normal water line but caused minimal flooding of the station itself. On Follets Island, located between Freeport and San Luis Pass, highwater overtopped highway 257 which is at an elevation of +8 ft (2.4 m) NGVD and caused numerous cuts through the dunes and sections of the roadbed. As described by Savage et. al., (2), these cuts were formed by highwater flowing from

Christmas Bay across the barrier island and out into the Gulf. The entire eastern tip of Follets Island at San Luis Pass appeared to have been inundated by the surge.

Between San Luis Pass and Jamaica Beach, 10 miles (16 km) to the east, the surge exceeded +9 ft (2.7 m) NGVD, overtopping Highway 257, the highest point on the western end of Galveston Island. Residences in this area exhibited extensive damage primarily from wind action. The total rise in water level reached approximately +11 ft (3.4 m) NGVD in Jamaica Beach and tapered to about +7 ft (2.1 m) NGVD near the western end of the Galveston seawall. Water levels rose from both the Gulf of Mexico and East Bay sides on this portion of the island but did not exceed the elevation of the coastal highway.

In the city of Galveston the storm surge did not exceed the +15 ft (4.6 m) NGVD elevation of the seawall. Storm damage was limited to wind damage, some wave overtopping of the seawall and flooding of low lying areas near the causeway on the bay side. At East Beach, seaward of the Galveston seawall, the surge reached approximately +7 ft (2.1 m) NGVD, causing extensive damage to residences and commerical buildings and leaving large debris piles at the base of the seawall. Surge levels on the Bolivar Peninsula reached +7 to +8 ft (2.1 to 2.4 m) NGVD between the western end of the peninsula and Crystal Beach, rising from both the Gulf and Bay sides of the peninsula but failing to inundate Highway 87 and many homes built on high ground along the highway. At High Island, 50 miles (80 km) east of the point of landfall, the surge reached +4 to +5 ft (1.2 to 1.5 m) NGVD flooding extensive low lying marsh areas and depositing large amounts of sand on Highway 87.

At Virginia Point, just north of Galveston Island, the surge covered the Gulf Freeway up to approximately +7 ft (2.1 m) NGVD, cutting off access to the island during the height of the storm. The Texas City Dike was overtopped along most of its length but the Texas City Levee system protected the city from surge induced flooding. The surge along this section of the bay is estimated to have been between +7 and +10 ft (2.1 and 3.0 m) NGVD. At Seabrook, 15 miles (24 km) north of Texas City, the storm surge reached approximately +9 ft (2.7 m) NGVD, the water level remained considerably higher than normal in this area for at least 3 days after landfall.

High water marks at Baytown indicated a surge at the north end of Galveston Bay of approximately +10 ft (3.0 m) NGVD. The water level in this area rose 3 to 4 ft (0.9 to 1.2 m) above normal by the morning of 17 August 1983 and remained several feet higher than normal for at least 3 days after landfall. East of Baytown, in the Houston Point area, the shoreline is backed by bluffs 15 ft to 20 ft (4.5 to 6.0 m) high which prevented significant surge damage. No distinct highwater marks were located in this area.

The maximum water level at Anahuac, in the northeast corner of the bay exceeded +8 ft (2.4 m) NGVD, flooding a Texas Water Resources Board recording tide gage. The topography in this area is flat and low lying, allowing the surge to propagate north past the Interstate 10 crossing of the Trinity River 7 miles (11 km) north of Anahuac.

Debris along the I-10 causeway indicated a surge level near +10 ft (3.0 m) NGVD. At Smith Point, 15 miles (24 km) south of Anahuac, high water marks in a county park indicated a rise in water level of approximately +5 ft (1.5 m) NGVD. Smith Point and the bay shoreline to the east are low lying wetland areas that were inundated by the surge except for high ground along Highway 562 and isolated highspots 5 to 10 ft (1.5 to 3.0 m) above NGVD.

FUTURE PLANS

While much of the coastline presently encompassed by the study is either accessible from inland or has some offshore structure suitable for semi-permanent instrumentation, there are some lengthy reaches where the only feasible means of data acquisition is by use of a temporarily deployed offshore device. To address this need, WES, with the assistance of the U. S. Army Research and Development Center, Natick, MA, has under development an air deployable wave/surge gage. The primary goal of this effort is the development of a launch vehicle and the methodology to successfully deploy the device from a C-130 type aircraft. Presently, the system is designed to accommodate acoustic or electromagnetic type water level and current meters.

In October, 1983, an agreement was reached with the National Hurricane Center (NHC) to provide manpower and equipment (trucks, helicopters, etc.) to deploy surge gages when a storm threatened the South Florida coastline. Since storms tend to travel parallel to the south Florida coast, a small error in predicted track can translate to a large error in point of landfall. The assistance of supplemental field teams allows coverage of a greater reach of coastline thereby increasing the probability that the storm will be intercepted.

Hopefully, more joint programs with District CE offices can be established to provide additional benefits to the surge data collection effort. Two field teams and twenty instrument packages will be maintained in a state of readiness for the next 3 to 4 hurricane seasons to collect data from any hurricane making landfall on the U. S. Gulf Coast. Individual data reports for each storm will be published by CERC.

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