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

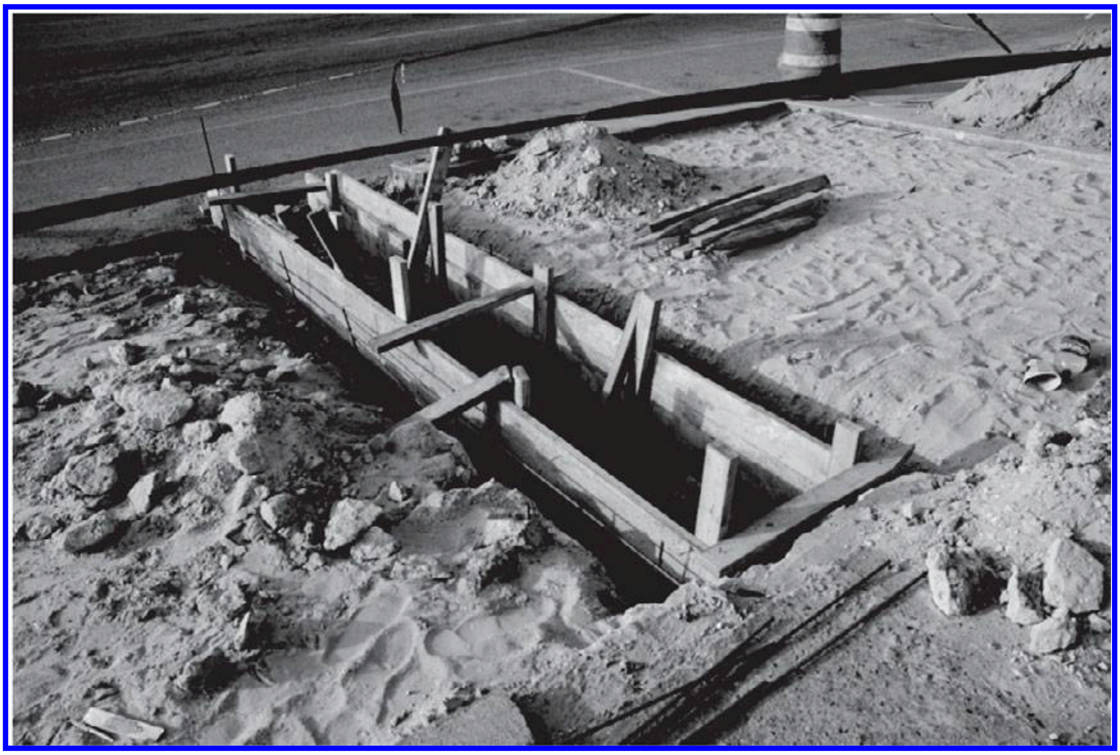

Figure 5-10. Repair of street drains that connect through the seawall

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.

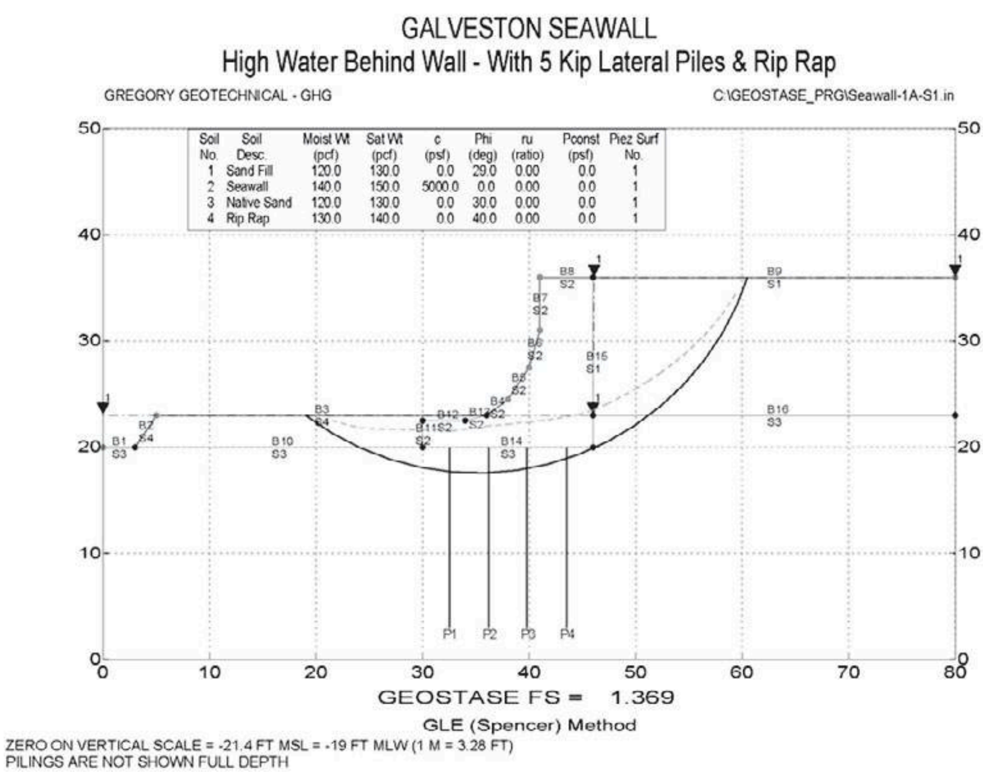

Figure 5-14. Stability analysis for Galveston Seawall with high water behind wall, 5 kip lateral piles, and rip rap toe protection

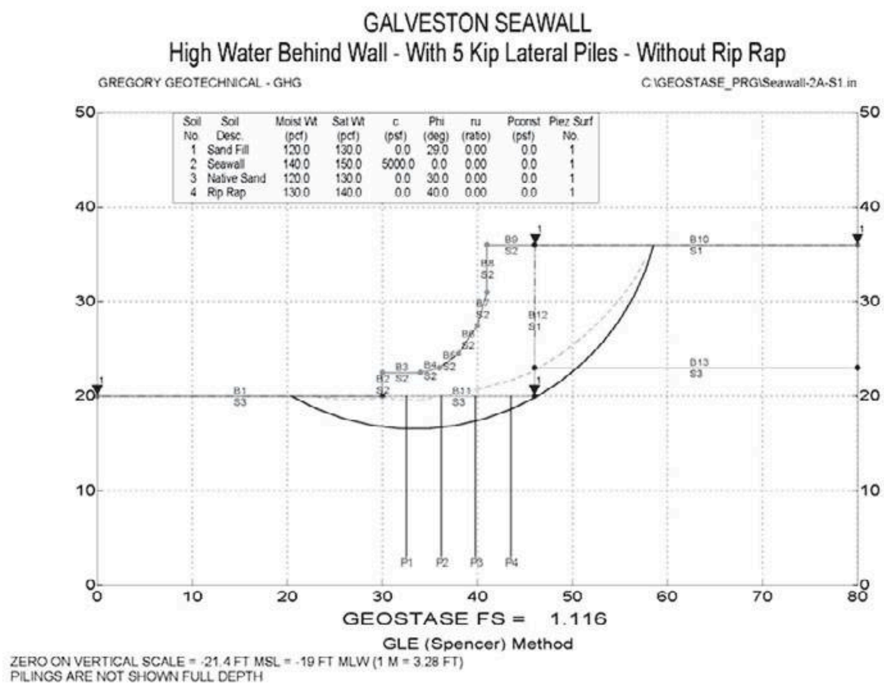

Figure 5-15. Stability analysis for Galveston Seawall with high water behind wall, 5 kip lateral piles, and without rip rap toe protection

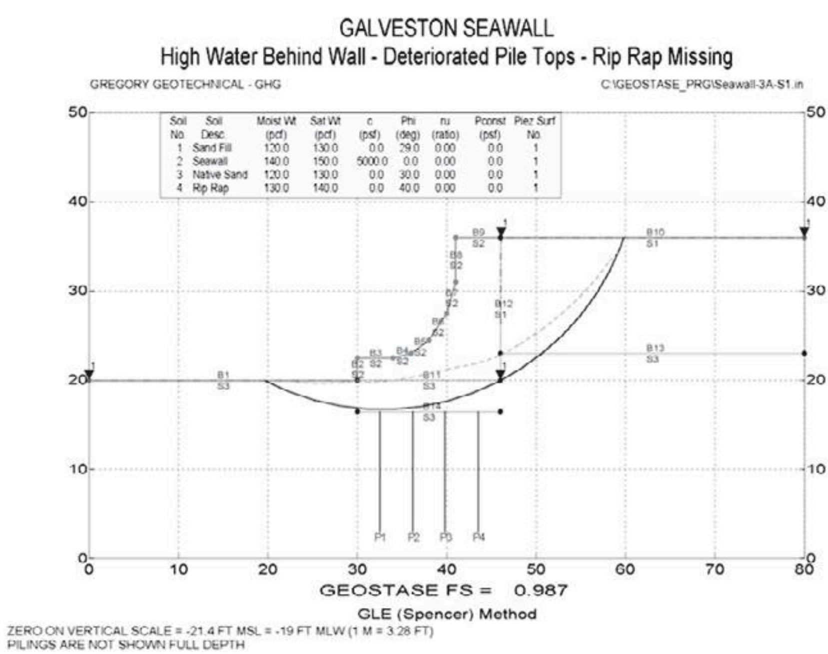

Figure 5-16. Stability analysis for Galveston Seawall with high water behind wall, deteriorated pile tops, and without rip rap toe protection

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

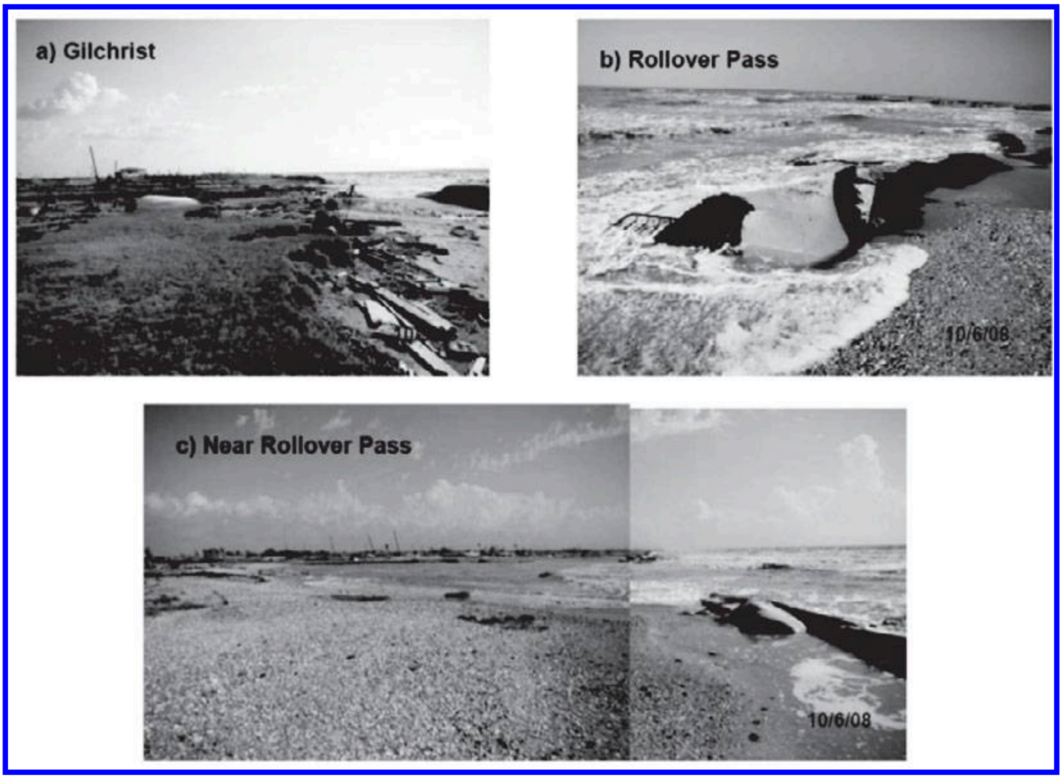

Figure 5-17. Geotextile tube performance on Bolivar Peninsula, (a) at Gilchrist, and (b) and (c) near Rollover Pass, showing shoreline erosion between gaps in structure

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).

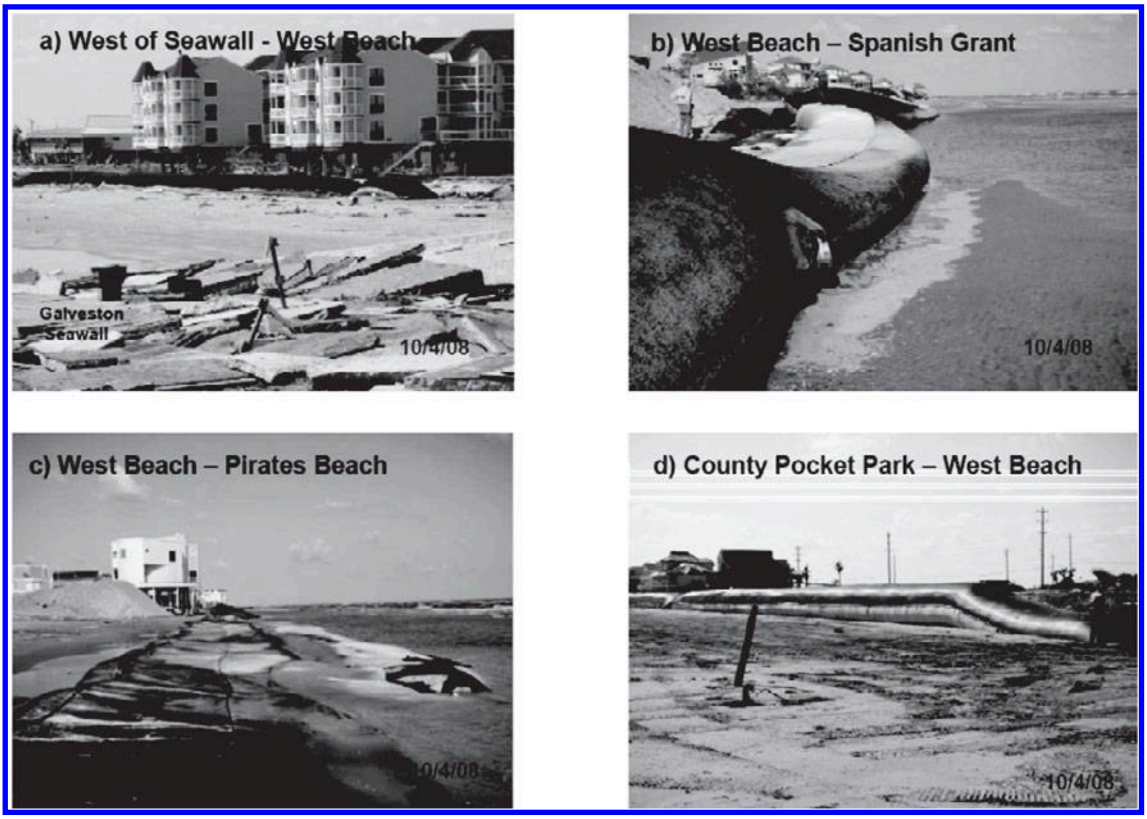

Figure 5-18. Performance of geotextile installations along Galveston Island, (a) just west of Galveston Seawall with gaps and exposed from erosion of dune, (b) at Spanish Grant showing collapse of top tube Gulfward, (c) cut and deflation of top tube leaving only base layer, and (d) intact but uncovered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

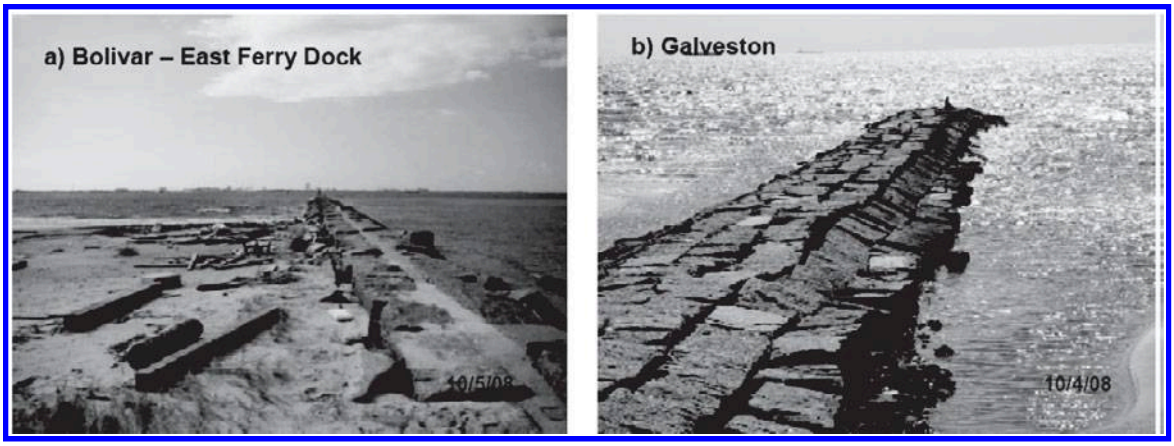

Figure 5-19. Groins at (a) Bolivar Peninsula and (b) along the Galveston Seawall showing little damage

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