Chapter 2: Historial Perspective

Table of Contents

Figures

Historical Perspective

2.1 Introduction

Through the years, FEMA and other agencies have documented and evaluated the effects of coastal flood events and the performance of coastal buildings during those events. These evaluations are useful because they provide a historical perspective on matters related to the siting, design, and construction of buildings along the Atlantic, Pacific, Gulf of Mexico, and Great Lakes coasts. They are useful also because they provide a baseline against which the impacts of later coastal flood events can be measured.

Within this context, several hurricanes, coastal storms, and other coastal flood events stand out as being especially important, either because of the nature and extent of the damage they caused or because of particular flaws they exposed in hazard identification, siting, design, construction, or maintenance practices. Many of these events—particularly the more recent ones—have been documented by FEMA in Flood Damage Assessment Reports and Building Performance Assessment Team (BPAT) reports.

This chapter describes coastal flood and wind events that have affected the continental United States, Alaska, Hawaii, and U.S. Territories since the beginning of this century. Findings of post-event building performance and damage assessments are summarized, as are the lessons learned regarding factors that contribute to flood and wind damage.

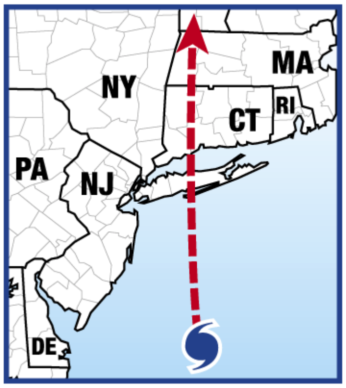
NOTE

Hurricane categories reported in this manual should be interpreted cautiously. Storm categorization based on wind speed may differ from that based on barometric pressure or storm surge. Also, storm effects vary geographically—only the area near the point of landfall will experience effects associated with the reported storm category.

2.2 Coastal Flood and Wind Events

2.2.1 Northeast Atlantic Coast

1938, September 21 – New England Hurricane. The 1938 hurricane was one of the strongest ever to strike New York and New England. Although the maximum sustained wind speed at the storm's peak was estimated at 140 mph, by landfall the wind speeds had diminished substantially (NOAA 1996). The storm, like most other hurricanes striking the area (e.g., Hurricane Gloria in 1985), had a forward speed in excess of 30 mph at the time of landfall, and it moved through the area rapidly. Despite its high forward speed, the storm caused widespread and significant damage to buildings close to the shoreline (see Figure 2-1) (surge and wave damage) and to buildings away from the coast (wind and tree-fall damage). Minsinger (1988) provides documentation of the storm and the damage it caused, which, according to NOAA (1997), rank this storm as the eighth most costly hurricane to strike the United States this century.



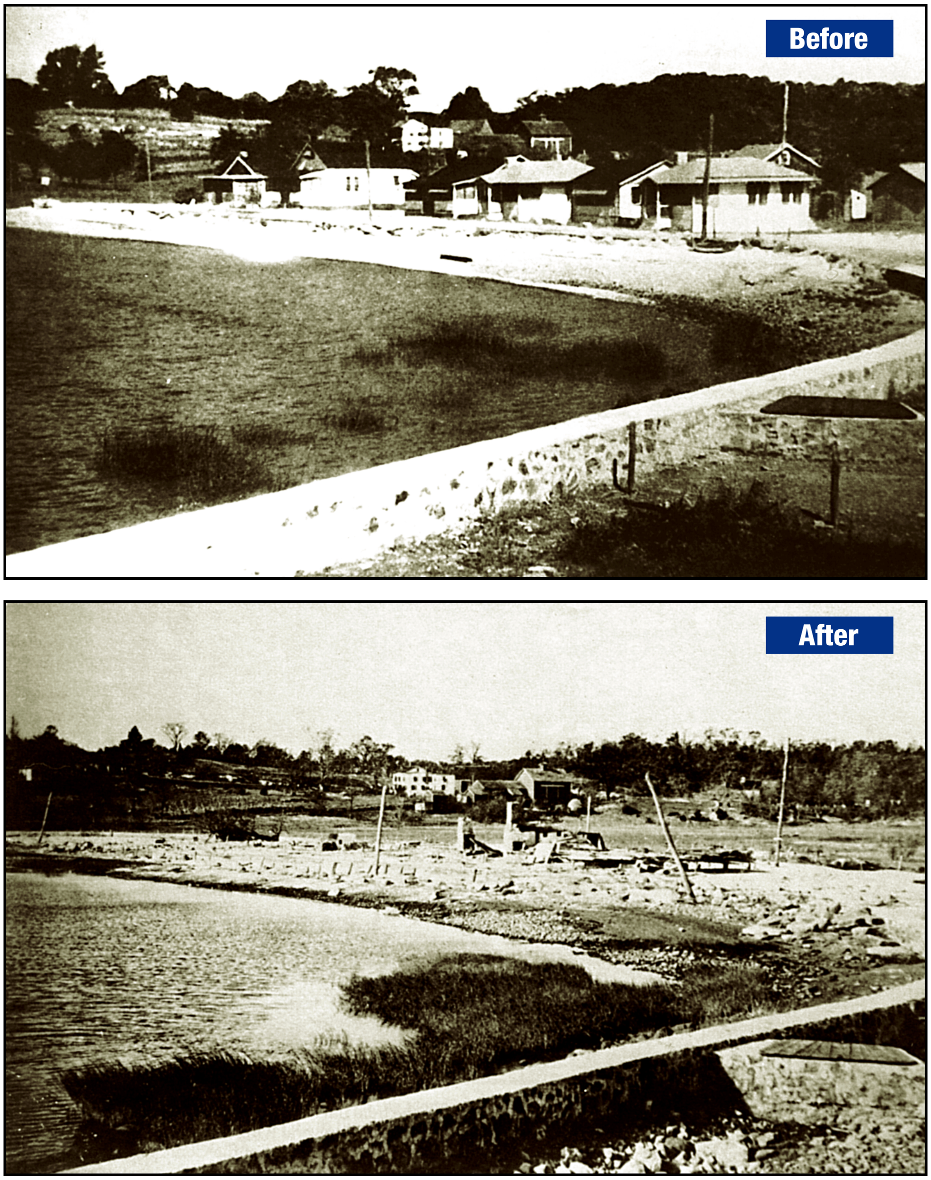


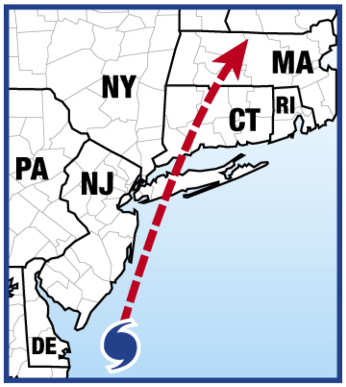
Figure 2-1
1938 Hurricane. Schell Beach, Guilford, Connecticut, before and after the storm. Unelevated houses at the shoreline were destroyed. WPA photograph, from Minsinger (1988).

1962, March 5-8 – Mid-Atlantic Northeaster. One of the most damaging storms on record, this northeaster affected almost the entire eastern seaboard of the United States and caused extreme damage in the mid-Atlantic region. As documented by Wood (1976), the high winds associated with this slow-moving storm included peak gusts of up to 84 mph and continued for 65 hours, through five successive high tides. The combination of sustained high winds with spring tides resulted in extensive flooding along the coast from the Outer Banks of North Carolina to Long Island, New York (see Figure 2-2). In many locations, waves 20 to 30 feet high were reported. The flooding caused severe beachfront erosion, inundated subdivisions and coastal industrial facilities, toppled beachfront houses and swept them out to sea, required the evacuation of coastal areas, destroyed large sections of coastal roads, and interrupted rail transportation in many areas. In all, property damage was estimated at half a billion dollars (in 1962 dollars).

Figure 2-2
1962 Mid-Atlantic storm. Extreme damage to homes along the beach at Point-o-Woods, Fire Island, New York. UPI/Corbis-Bettmann photograph.

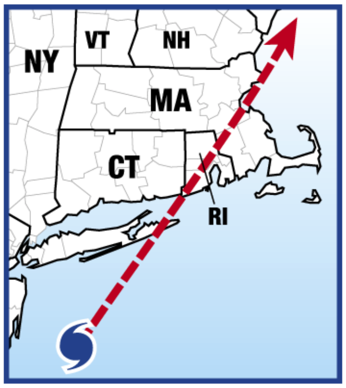
1984, March 29 – Northeaster, New Jersey. On March 28, 1984, a large low-pressure system developed in the southeastern United States and strengthened dramatically as it moved across Tennessee, Kentucky, and Virginia. In the early morning hours of March 29, the storm system moved northeastward past the Delmarva Peninsula, gaining additional strength from the Atlantic Ocean. The storm continued tracking to the northeast with near hurricane-force winds (sustained winds ranged from 40 to 60 mph). The barometric pressure dropped from a normal of 29.92 inches to 28.5 inches, and it was estimated that tides along the New Jersey coast ranged from 4 to 7 feet above normal at high tide (USDC, NOAA 1984). Measurements of local tidal flooding indicate that this storm had a recurrence interval of approximately 10–20 years (NJDEP 1986).

In its 1986 Hazard Mitigation Plan, the New Jersey Department of Environmental Protection reported the following regarding damage from the 1984 storm (NJDEP 1986): "In general, damage along the oceanfront from this storm varied depending on whether beaches and dunes were present or absent. In more structurally fortified areas with seawalls, bulkheads, and revetments, areas usually with little or no beach, there was more structural and wave damage. In areas of moderate beaches with little or no dune protection, particularly at street ends, there was significant overwash of sand into streets and property, in addition to severe beach erosion. There was also significant amounts of sand blown down streets and onto adjacent properties in areas where there were unvegetated dunes. In areas with wider beaches and cultivated dunes, damage was limited to the ubiquitous beach erosion and scarping (or cliffing) of dunes. Because of the short duration of the storm, there was remarkably little structural damage to private homes. Undoubtedly, better building practices and better dunes instituted since the 1962 storm contributed to this fairly low loss. In more inland areas, along the baysides behind the barriers, there was significant flooding from the elevated tidal waters. Although evacuations were called for in many areas, low causeways and highways, particularly in Atlantic County, made evacuations impossible."



1985, September 27 – Hurricane Gloria, New York. This fast-moving hurricane crossed Long Island near the time of low tide, causing minor storm surge and erosion damage, but substantial wind damage. Storm impacts were documented in the first of many FEMA Post-Flood Disaster Assessment Reports. The report (URS 1986) concluded the following:

- Wind speeds on Long Island may have exceeded the code-specified 75 mph (fastest-mile) wind speed.
- Tree damage, which was widespread and substantial, led to loss of overhead utility lines and damage to buildings.
- Common causes of failures in residential construction included poor roof-to-wall connections, lack of hurricane clips, flat roofs, eaves greater than 18 inches, and large plate glass windows facing seaward.
- The density of development, combined with high incidence of first-row roof failures, led to significant debris and projectile damage to second- and third-row buildings.
- Oceanfront areas had been left vulnerable to flood, erosion, and wave damage by previous northeast storms. Accordingly, damage from Gloria included settlement of inadequately embedded pilings, loss of poorly connected beams and joists, failure of septic systems due to erosion, and water and overwash damage to non-elevated buildings.



1991, August 19 – Hurricane Bob, Buzzards Bay Area, Massachusetts. Hurricane Bob, a Category 2 hurricane, followed a track similar to that of the 1938 New England hurricane. Although undistinguished by its intensity (not even ranking in the 65 most intense hurricanes to strike the United States during the 20th century), it caused $1.75 billion in damage (1996 dollars) (see Figure 2-3), ranking 18th in terms of damage (NOAA 1997). A FEMA Flood Damage Assessment Report (URS 1991c) documented damage in the Buzzards Bay area. The wind speeds during Hurricane Bob were below the design wind speed and the storm tide (corresponding to a 15-year tide) was at least 5 feet below the Base Flood Elevation (BFE). Nevertheless the results of the storm allowed an evaluation of the performance of different foundation types.

- Many buildings in the area had been elevated on a variety of foundations, either in response to Hurricane Carol (1954) or the 1978 northeaster, or as a result of community-enforced NFIP requirements.
- Buildings constructed before the date of the Flood Insurance Rate Map (FIRM) for each community—referred to as *pre-FIRM* buildings—that had not been elevated, or that had not been elevated sufficiently, suffered major damage or complete destruction; some destroyed buildings appeared to have had insufficient foundation embedment.
- Post-FIRM buildings (i.e., built after the date of the FIRM) and pre-FIRM buildings with sufficient elevation performed well during the storm. Where water was able to pass below buildings unobstructed by enclosed foundations, damage was limited to loss of decks and stairs.

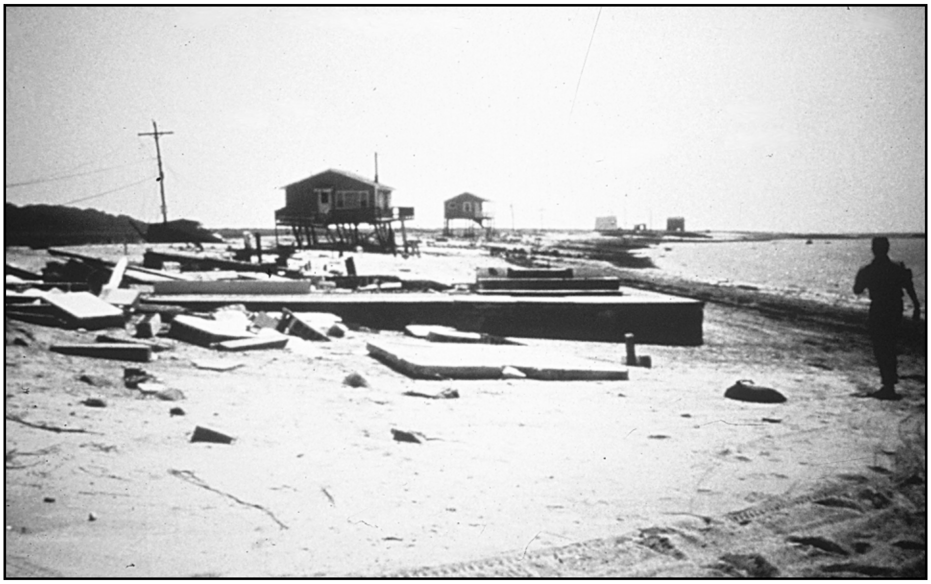


Figure 2-3
Hurricane Bob (1991) destroyed 29 homes along this reach of Mattapoisett, Massachusetts. Photograph by Jim O'Connell.

- Foundation types that appeared to survive the storm without structural damage included the following:
    a) cast-in-place concrete columns, at least 10 inches in diameter
    b) masonry block columns with adequate embedment depth
    c) 10-inch-thick shear walls with a flow-through configuration (open ends) or modified to include garage doors at each end of the building (intended to be open during a storm)

1991, October 31 – Northeaster, Long Island, New York, and Boston, Massachusetts. This storm, which followed closely on the heels of Hurricane Bob, was one of the most powerful northeasters on record and is described in papers by Dolan and Davis (1992) and Davis and Dolan (1991). A FEMA Flood Damage Assessment Report (URS 1992) documented damage to buildings along the south shore of Long Island and in the Boston area, and noted the following:

- Pre-FIRM at-grade buildings were generally subject to erosion and collapse; however, at least one was partially buried by several feet of sand overwash.
- Some buildings were damaged by floodborne debris from other damaged structures.
- Some pile-supported buildings sustained damage as a result of inadequate pile embedment; some settled unevenly into the ground as a result of loss of bearing capacity; some were damaged as a result of collapse of the *landward* portion of the foundation (the seaward portion had been repaired after recent storms, while the landward portion was probably original and less deeply embedded).
- In areas subject to long-term erosion, buildings became increasingly vulnerable to damage or collapse with each successive storm.
- Although erosion control structures provided protection to many buildings, some buildings landward of revetments or bulkheads were damaged as a result of wave overtopping and erosion behind the erosion control structures.
- Buildings atop continuous masonry block foundations (such as those permitted in A zones) commonly were damaged or destroyed when exposed to flooding, wave action, erosion, and/or localized scour (see Figure 2-4).
- Buildings atop continuous cast-in-place concrete foundations performed better than those atop continuous masonry block foundations, and were generally more resistant to wave and flood damage; however, some continuous cast-in-place concrete foundations were damaged as a result of the footing being undermined by erosion and localized scour.

Figure 2-4
October 1991 northeaster damage to homes at Scituate, Massachusetts. Photograph by Jim O'Connell.

1992, January 4 – Northeaster, Delaware and Maryland. This northeaster was the most intense and damaging in coastal Delaware and Maryland since the Ash Wednesday1962 northeaster. A FEMA Building Performance Assessment Team (BPAT) inspected damage in six Delaware and Maryland communities (see Figure 2-5). In its report (FEMA 1992), the BPAT concluded the following:

- Damage was principally due to storm surge, wave action, and erosion. Beaches affected by the January storm had not fully recovered from the Halloween 1991 storm, which left coastal areas vulnerable to further damage.

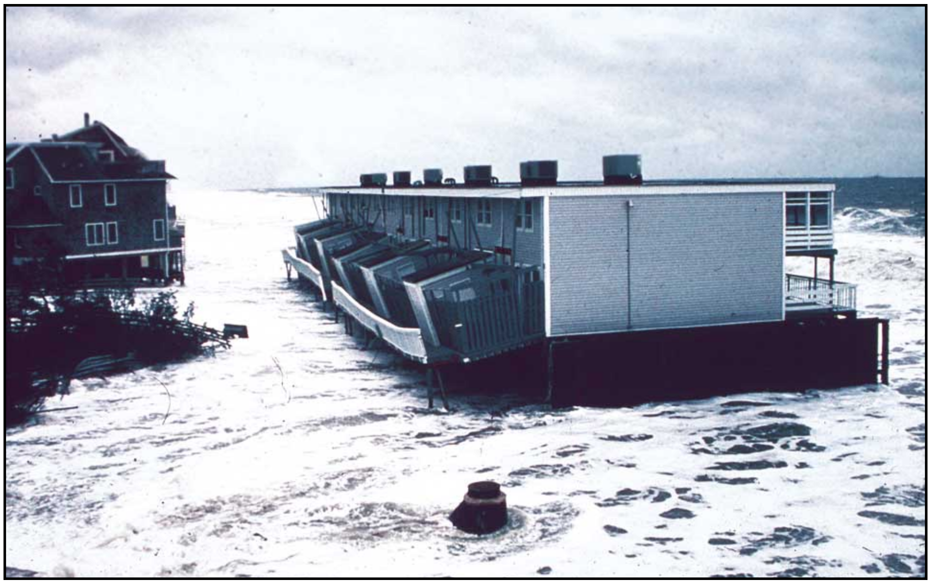


Figure 2-5
1992 storm impacts at Dewey Beach, Delaware. Note collapse of deck on landward side of building. Photograph by Anthony Pratt.

- Those buildings constructed to NFIP requirements fared well during the storm. For those buildings damaged, a combination of ineffective construction techniques and insufficient building elevation appeared to be the major causes of damage.
- For some pile-supported buildings, inadequate connection of floor joists to beams led to building damage or failure. Obliquely incident waves are believed to have produced non-uniform loads and deflections on pile foundations, causing non-uniform beam deflections and failure of inadequate joist-to-beam connections. The report provides three possible techniques to address this problem.
- Some buildings had poorly located or fastened utility lines. For example, some sewer stacks and sewer laterals failed as a result of erosion and flood forces. The report provides guidance on location and fastening of sewer connections to minimize vulnerability.
- Many pile-supported buildings were observed to have sustained damage to at-grade or inadequately elevated mechanical equipment, including air conditioning compressors, heat pumps, furnaces, ductwork, and hot water heaters. The report provides guidance on proper elevation of these units.

2.2.2 Southeast Atlantic Coast and Caribbean

1926, September 18 – Hurricane, Miami, Florida. Those who believe we have only recently come to understand storm-resistant design and construction will be surprised by the insight and conclusions contained in a 1927 article by Theodore Efting, a south Florida engineer, 1 year after the 1926 hurricane (see Figure 2-6) struck Miami, Florida (Eefting 1927). The article points out many weaknesses in buildings and construction that we still discuss today:

- light wooden truss roof systems and truss-to-wall connections
- faults and weaknesses in windows and doors, and their attachment to the main structure
- poor quality materials
- poor workmanship, supervision, and inspection
- underequipped and undermanned building departments

Eefting makes specific comments on several issues that are still relevant:

> Buildings under three stories in height – "… the most pertinent conclusion that may be reached is that the fault lies in the actual construction in the field, such as lack of attention to small detail, anchors, ties, bracing, reinforcing, carpentry, and masonry work."
>
> The role of the designer – "Engineers and architects are too prone to write specifications in which everything is covered to the minutest

detail, and to draw plans on which requirements are shown with hair splitting accuracy, and then allow the contractor to build the building, sewer, pavement or structure in general with little or no supervision."

Building codes – "In the repeated emphasis on inspection and the importance of good workmanship we should not lose sight of the value of good building codes. . . Every city in the state whether damaged by the storm or not would do well to carefully analyze the existing codes and strengthen them where weak."

Figure 2-6
Building damage from 1926 hurricane, Miami, Florida.

1988, April 13 – Northeaster, Sandbridge Beach, Virginia, and Nags Head, North Carolina. This storm, although not major, resulted in damage to several piling-supported oceanfront houses in North Carolina and Virginia. Long-term shoreline erosion coupled with the effects of previous coastal storms (January 1987, February 1987, April 8, 1988) left these areas vulnerable to the erosion caused by the April 13 storm. The Flood Damage Assessment Report completed after the storm (URS 1989) concluded the following:

- The storm produced sustained winds in excess of 30 mph for over 40 hours; storm tide stillwater levels were approximately 3 feet above normal; the dune face retreated landward 20 to 60 feet in places.
- Several pile-supported single-family houses sustained damage to decks and main structures as a result of insufficient pile penetration; in North Carolina, the affected houses appeared to predate 1986 North Carolina Building Code pile embedment requirements.
- Post-storm inspections revealed that foundations of many of the affected houses had been repaired previously (by jetting of new piles and splicing/bolting to old piles; addition of cross-bracing; addition of timber grade beams). Previous repairs were only partially effective in preventing structural damage during the storm.

- Followup examinations of some of the houses in August 1988 showed the same types of foundation repairs used previously.
- Standard metal hurricane clips and joist hangers were observed to have suffered significant to severe corrosion damage. Alternative connectors – such as heavier gauge connectors, wooden anchors, or noncorrosive connectors – should be used in oceanfront areas.

1989, March 6-10 – Northeaster, Nags Head, North Carolina, Kill Devil Hills, North Carolina, and Sandbridge Beach, Virginia. Damage from the March 1989 northeaster was much greater than that caused by the April 1988 storm, despite lower peak wind speeds and storm surge during the latter event. The increased damage was caused by a longer storm duration (sustained winds of 33 mph for over 59 hours) coincident with spring tides. The storm reportedly destroyed or damaged over 100 cottages and motels.

In addition to reaffirming the conclusions of the FEMA report of the April 1988 storm (URS 1989), the March 1989 FEMA Flood Damage Assessment Report (URS 1990) concluded the following:

- Once undermined, plain concrete slabs, and grade beams cast monolithically with them, failed under their own weight or as a result of wave and debris loads (see Figure 2-7).
- Failure of the pile-to-beam connection was observed where a bolt head lacked a washer and pulled through the beam.
- Cracks in, or failed connections to, piles and deck posts were, in some cases, attributed to cross-bracing oriented parallel to the shore or the attachment of closely spaced horizontal planks.
- Construction in areas subject to high rates of long-term erosion is problematic. Buildings become increasingly vulnerable to the effects of even minor storms (see Figure 2-8). This process eventually necessitates their removal or results in their destruction.
- Many of the buildings affected during the April 1988 storm were further damaged during the March 1989 storm, because of either additional erosion and undermining or debris damage to cross-bracing and foundation piles (see Figures 2-9 and 2-10).

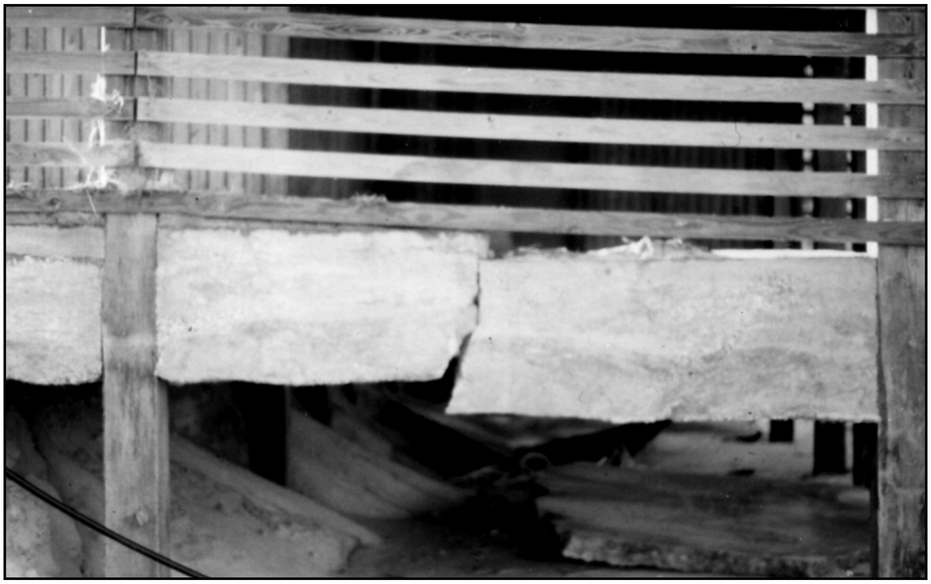


Figure 2-7
March 1989 northeaster. This plain concrete perimeter grade beam cracked in several places.

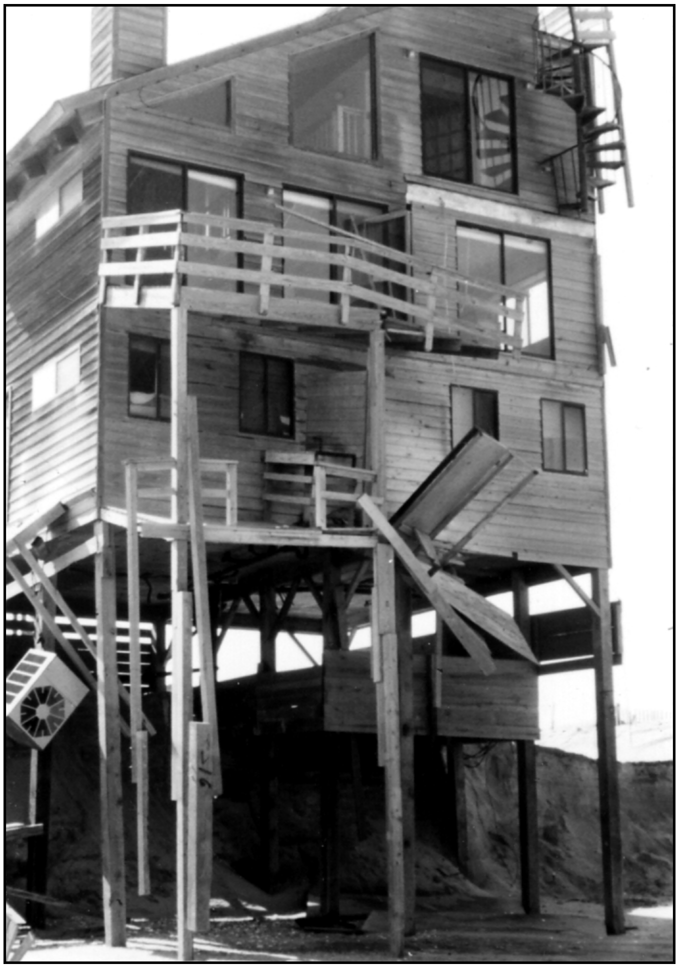
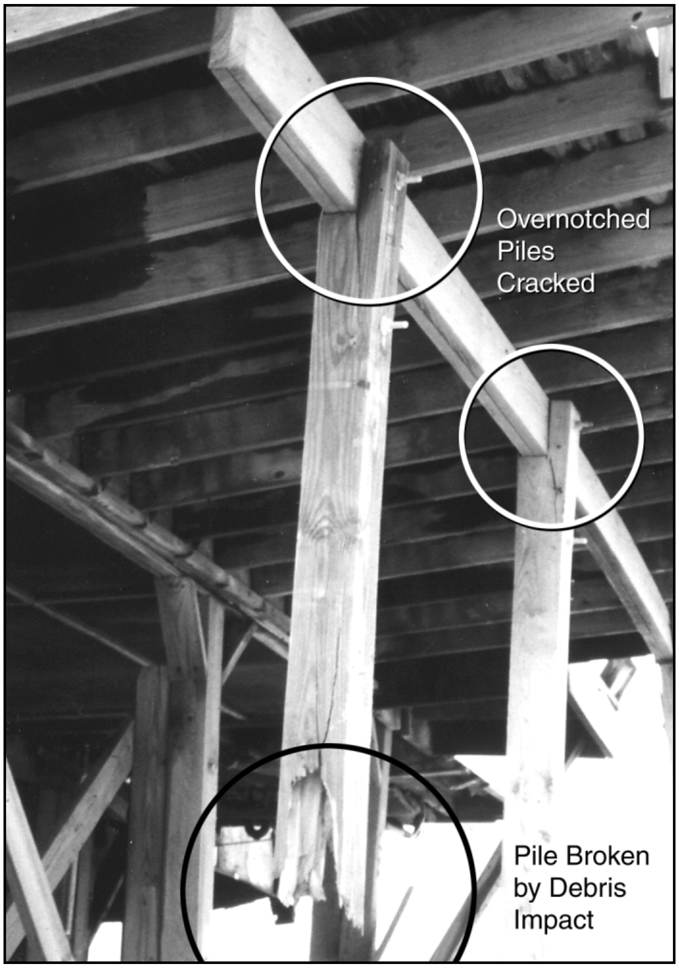


Figure 2-8
March 1989 northeaster. Although this house seems to have lost only several decks and a porch, the loss of supporting soil leaves its structural integrity in question.

Figure 2-9
March 1989 northeaster.
Failure of cross-bracing.

Figure 2-10
March 1989 northeaster.
Deck pile broken by debris impact. Flood forces also caused piles to crack at overnotched connections to floor beam.



1989, September 21-22 – Hurricane Hugo, South Carolina. Hurricane Hugo was one of the strongest hurricanes known to have struck South Carolina. Widespread damage was due to a number of factors: flooding, waves, erosion, debris, and wind. In addition, building and contents damage caused by rainfall penetration into damaged buildings, several days after the hurricane itself, often exceeded the value of direct hurricane damage.

Damage from, and repairs following, Hugo were documented in a FEMA Flood Damage Assessment Report (URS 1991a) and a Follow-Up Investigation Report (URS 1991b). The reports concluded the following:

- Post-FIRM buildings that were both properly constructed and elevated survived the storm (see Figure 2-11). These buildings stood out in sharp contrast to pre-FIRM buildings and to post-FIRM buildings that were poorly designed or constructed.

Figure 2-11
Hurricane Hugo (1989), Garden City Beach, South Carolina. House on pilings survived while others did not.

- Many buildings elevated on masonry or reinforced concrete columns supported by shallow footings failed. In some instances, the columns were undermined; in others, the columns failed as a result of poor construction (see Figure 2-12).
- Several pile-supported buildings not elevated entirely above the wave crest showed damage or destruction of floor beams, floor joists, floors, and exterior walls.
- Some of the most severely damaged buildings were in the second, third, and fourth rows back from the shoreline. These areas were mapped as A zones on the FIRMs for the affected communities. Consideration should be given to more stringent design standards for coastal A zones.

- The storm exposed many deficiencies in residential roofing practices: improper flashing, lack of weather-resistant ridge vents, improper shingle attachment, and failure to replace aging roofing materials.

Figure 2-12
Hurricane Hugo (1989), South Carolina. Failure of reinforced masonry column.

1992, August 24 – Hurricane Andrew, Dade County, Florida. Hurricane Andrew was a strong Category 4 hurricane when it made landfall in southern Dade County and caused over $26 billion in damage (NOAA 1997). The storm is the third most intense hurricane to strike the United States in the 20th century and remains the most costly natural disaster to date. The storm surge and wave effects of Andrew were localized and minor when compared with the damage due to wind. A FEMA Building Performance Assessment Team evaluated damage to one- to two-story wood-frame and/or masonry residential construction in Dade County. In its report (FEMA 1993a), the team concluded the following:

- Buildings designed and constructed with components and connections that transferred loads from the envelope to the foundation performed well. When these critical “load transfer paths” were not in evidence, damage ranged from considerable to total, depending on the type of architecture and construction.
- Catastrophic failures of light wood-frame buildings were observed more frequently than catastrophic failures of other types of buildings constructed on site. Catastrophic failures were due to a number of factors:
    a) lack of bracing and load path continuity at wood-frame gable ends
    b) poor fastening and subsequent separation of roof sheathing from roof trusses

   c) inadequate roof truss bracing or bridging (see Figure 2-13)
   d) improper sillplate-to-foundation or sillplate-to-masonry connections

Figure 2-13
Hurricane Andrew (1992). Roof structure failure due to inadequate bracing.

- Failures in masonry wall buildings were usually attributable to one or more of the following:
   a) lack of or inadequate vertical wall reinforcing
   b) poor mortar joints between masonry walls and monolithic slab pours
   c) lack of or inadequate tie beams, horizontal reinforcement, tie columns, and tie anchors
   d) missing or misplaced hurricane straps between the walls and roof structure
- Composite shingle and tile (extruded concrete and clay) roofing systems sustained major damage during the storm. Failures were usually due to improper attachment, impacts of windborne debris, or mechanical failure of the roof covering itself.
- Loss of roof sheathing and consequent rainfall penetration through the roof magnified damage by a factor of five over that suffered by buildings whose roofs remained intact or suffered only minor damage (Sparks, et al. 1994).
- Exterior wall opening failures (particularly garage doors, sliding glass doors, French doors, and double doors) frequently led to internal pressurization and structural damage. Storm shutters and the covering of windows and other openings reduced such failures significantly.

- Quality of workmanship played a major role in building performance. Many well-constructed buildings survived the storm intact, even though they were adjacent to or near other buildings that were totally destroyed by wind effects.

1995, September 15-16 – Hurricane Marilyn, U.S. Virgin Islands and Puerto Rico. Hurricane Marilyn struck the U.S. Virgin Islands on September 15-16, 1995. With sustained wind speeds of 120 to 130 mph, Marilyn was classified a Category 3 hurricane. The primary damage from this storm was caused by wind; little damage was caused by waves or storm surge.

As documented by the National Roofing Contractors Association (NRCA 1996), most of the wind damage consisted of either the loss of roof sections (see Figure 2-14)—usually metal decking installed on purlins attached to roof beams spaced up to 48 inches on center—or failures of gable ends. In addition, airborne debris penetrated roofs (see Figure 2-15) and unprotected door and window openings. This damage allowed wind to enter buildings and cause structural failures in roofs and under-reinforced walls. Near the tops of high bluffs, wind speedup effects resulted in damage that better represented 140-mph sustained winds.

Figure 2-14
Hurricane Marilyn (1995). This house lost most of the metal roof covering. Neighbors stated that the house also lost its roof covering during Hurricane Hugo, in 1989.

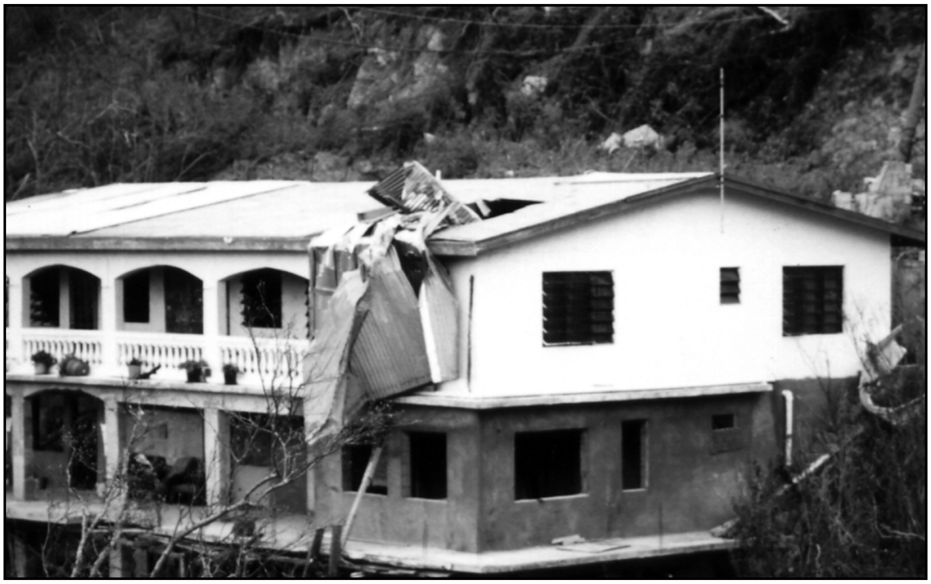


Figure 2-15
Hurricane Marilyn (1995). The roof of this house was penetrated by a large wind-driven missile (metal roof covering).

1996, September 5 – Hurricane Fran, Southeastern North Carolina. Hurricane Fran, a Category 3 hurricane, made landfall near Cape Fear, North Carolina. Erosion and surge damage to coastal construction were exacerbated by the previous effects of a weaker storm, Hurricane Bertha, which struck 2 months earlier. A FEMA Building Performance Assessment Team (BPAT) reviewed building failures and successes and concluded the following (FEMA 1997):

- Many buildings in mapped A zones were exposed to conditions associated with V zones, which resulted in building damage and failure from the effects of erosion, high-velocity flow, and waves. Remapping of flood hazard zones after the storm, based on analyses that accounted for wave runup, wave setup, and dune erosion, resulted in a significant landward expansion of V zones.
- Hundreds of oceanfront houses were destroyed by the storm, mostly as a result of insufficient pile embedment (see Figure 2-16) and wave effects. Most of the destroyed buildings had been constructed under an older building code provision that required that piling foundations extend only 8 feet below the original ground elevation. Erosion around the destroyed oceanfront foundations was typically 5–8 feet. In contrast, foundation failures were rare in similar, piling-supported buildings located farther from the ocean and not subject to erosion.
- A significant reduction in building losses was observed in similarly sized oceanfront buildings constructed after the North Carolina Building Code was amended in 1986 to require a minimum embedment to –5.0 feet National Geodetic Vertical Datum (NGVD) or 16 feet below the original ground elevation, whichever is shallower, for

CROSS-REFERENCE

Figure 3-10, in Chapter 3, shows how a restudy of coastal hazards after a severe storm such as Hurricane Fran can result in significantly different flood hazard mapping. The more extensive V zone on the post-Fran FIRM shown in Figure 3-10 is due in part to the topographic changes caused by storm-induced erosion.

pilings near the ocean. A study of Topsail Island found that 98 percent of post-1986 oceanfront houses (200 of 205) remained after the hurricane. Ninety-two percent of the total displayed no significant damage to the integrity of the piling foundation. However, 5 percent (11) were found to have leaning foundations (see Figure 2-16). A non-destructive test used to measure piling length in a partial sample of the leaning buildings revealed that none of the leaning pilings tested met the required piling embedment standard. Many were much shorter. However, given the uncertainty of predicting future erosion, the BPAT recommended that consideration be given to a piling embedment standard of –10.0 feet NGVD.

Figure 2-16
Hurricane Fran (1996). Many oceanfront houses built before the enactment of the 1986 North Carolina State Code were found to be leaning or destroyed.

- The BPAT noted a prevalence of multi-story decks and roofs supported by posts resting on elevated decks; these decks, in turn, were often supported by posts or piles with only 2–6 feet of embedment. Buildings with such deck and roof structures often sustained extensive damage when flood forces caused the deck to separate from the main structure or caused the loss of posts or piles and left roofs unsupported.

- Design or construction flaws were often found in breakaway walls. These flaws included the following:
    a) excessive connections between breakaway panels and the building foundation (however, the panels were observed generally to have failed as intended)

    b) placement of breakaway wall sections immediately seaward of foundation cross-bracing

    c) attachment of utility lines to breakaway wall panels
- Wind damage to poorly connected porch roofs and large roof overhangs was frequently observed.
- Corrosion of galvanized metal connectors (e.g., hurricane straps and clips) may have contributed to the observed wind damage to elevated buildings.
- As has been observed time and time again following coastal storms, properly designed and constructed coastal residential buildings generally perform well. Damage to well-designed, well-constructed buildings usually results from the effects of long-term erosion, multiple storms, large debris loads (e.g., parts of damaged adjacent houses), or storm-induced inlet formation/modification.

1998, September 21-22 – Hurricane Georges, Puerto Rico. On the evening of September 21, 1998, Hurricane Georges made landfall on Puerto Rico's east coast as a strong Category 2 hurricane. Wind speeds for Georges reported by the National Weather Service (NWS) varied from 109 mph to 133 mph (3-sec peak gust at a height of 33 feet). Traveling directly over the interior of the island in an east-to-west direction, George caused extensive damage. Over 30,000 homes were destroyed, and 50,000 more suffered minor to major damage.

A Building Performance Assessment Team deployed by FEMA conducted aerial and ground investigations of residential and commercial building performance. The team evaluated concrete and masonry buildings, including those with concrete roof decks and wood-frame roof systems, combination concrete/masonry and wood-frame buildings, and wood-frame buildings. The team's observations and conclusions include the following (FEMA 1999b):

- Many houses suffered structural damage from high winds, even though recorded wind data revealed that the wind speeds associated with Hurricane Georges did not exceed the basic design wind speed of the Puerto Rico building code in effect at the time the hurricane struck.
- Wind-induced structural damage in the observed buildings was attributable primarily to the lack of a continuous load path from the roof structure to the foundation.

- Concrete and masonry buildings, especially those with concrete roof decks, generally performed better than wood-frame buildings; however, the roofs of concrete and masonry buildings with wood-frame roof systems were damaged when a continuous load path was lacking.
- Coastal and riverine flood damage occurred primarily to buildings that had not been elevated to or above the BFE (see Figure 2-17).
- Flood damage to concrete and masonry structures was usually limited to foundation damage caused by erosion, scour, and the impact of waterborne debris.
- Although some examples of successful mitigation were observed, such as the use of reinforced concrete and masonry exterior walls, too little attention had been paid to mitigation in the construction of the observed houses.
- While not all of the damage caused by Hurricane Georges could have been prevented, a significant amount could have been avoided if more buildings had been constructed to meet the requirements of the Puerto Rico building code and floodplain management regulations in effect at the time the hurricane struck the island.

As a result of recommendations made by the FEMA Building Performance Assessment Team, the Government of Puerto Rico passed emergency, and subsequently final, regulations that repealed the existing building code and adopted the 1997 Uniform Building Code (UBC) as an interim step toward adopting the International Building Code (IBC) when it becomes available in early 2000.

Figure 2-17
Hurricane Georges (1998). Coastal building in Puerto Rico damaged by storm surge and waves.

2.2.3 Gulf of Mexico Coast

1900, September 8 – Galveston, Texas. This Category 4 hurricane was responsible for over 8,000 deaths—it is the most deadly natural disaster to affect the United States. The storm caused widespread destruction of much of the development on Galveston Island and pointed out the benefits of siting construction away from the shoreline. As a result, the city completed the first, large-scale retrofitting project (see Figure 2-18): roads and hundreds of buildings were elevated, ground levels in the city were raised several feet with sand fill, and the Galveston seawall was built (Walden 1990).

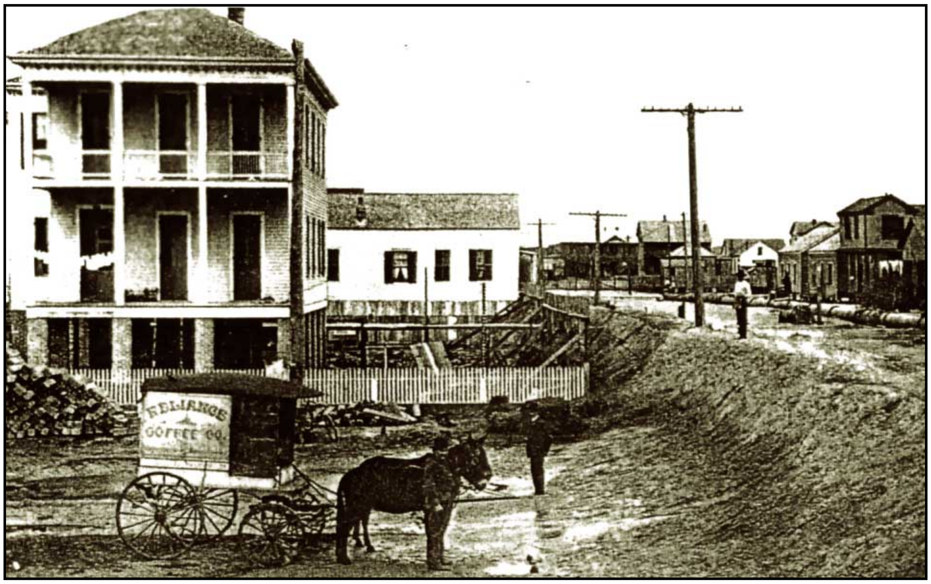


Figure 2-18
Galveston on two levels—the area at the right has already been raised; on the left, houses have been lifted, but the land is still low. Photograph courtesy of the Rosenberg Library, Galveston, Texas.

1961, September 7 – Hurricane Carla, Texas. Hurricane Carla was one of the 10 most intense hurricanes to strike the United States this century. This large, slow-moving Category 4 hurricane caused widespread erosion along the barrier islands of the central Texas coast. Storm surges reached 12 feet on the open coast and 15–20 feet in the bays. Hayes (1967) provides an excellent description of the physical effects of the storm on the barrier islands, where dunes receded as much as 100 feet, where barrier island breaching and inlet formation were commonplace, and where overwash deposits were extensive. The storm and its effects highlight the need for proper siting and construction in coastal areas.

1969, August 17 – Hurricane Camille, Mississippi and Alabama. Hurricane Camille was the second Category 5 hurricane to strike the United States and the most intense storm to strike the Gulf Coast during the 20th century. According to Thom and Marshall (1971), the storm produced winds with a recurrence interval of close to 200 years and storm tides that exceeded 200-year elevations in the vicinity of Pass Christian and Gulfport, Mississippi.

Thom and Marshall characterize observed wind damage as “near total destruction” in some sections of Pass Christian and Bay St. Louis, but “surprisingly light” in areas well back from the beach – this may have been due to the relatively small size of Camille and its rapid loss of strength as it moved inland. The aerial reconnaissance performed by Thom and Richardson indicated an extremely high incidence of damage to low, flat-roofed buildings. With few exceptions, they also found that residential buildings near the beach were totally destroyed by waves or storm surge; wave damage to commercial and other buildings with structural frames was generally limited to first-floor windows, and spandrel walls and partitions.

Several publications produced after Hurricane Camille documented typical wind damage to buildings (e.g., Zornig and Sherwood 1969, Southern Forest Products Association [undated], Saffir 1971, Sherwood 1972). The publications also documented design and construction practices that resulted in buildings capable of resisting high winds from Camille. Pertinent conclusions from these reports include the following:

- The structural integrity of wood buildings depends largely on good connections between components.
- Wood can readily absorb short-duration loads considerably above working stresses.
- Six galvanized roofing nails should be used for each three-tab strip on asphalt and composition roof shingles.
- Block walls with a u-block tie beam at the top do not sufficiently resist lateral loads imposed by high hurricane winds.
- Adding a list of shape factors for roof shape and pitch would strengthen the wind provisions of the building code.
- Many homes built with no apparent special hurricane-resistant construction techniques exhibited little damage, because the openings were covered with plywood “shutters.”
- The shape of the roof and size of the overhang seem to have had a major effect on the extent of damage.

1979, September 12 – Hurricane Frederic, Alabama. Hurricane Frederic was a Category 3 hurricane that made landfall at Dauphin Island. Storm surge, wave, erosion, and wind effects of the storm caused widespread damage to non-elevated and elevated buildings (see Figure 2-19) (USACE 1981). For example, a post-storm assessment of coastal building damage (FEMA 1980) found that over 500 homes were destroyed along the 22-mile reach from Fort Morgan through Gulf Shores.

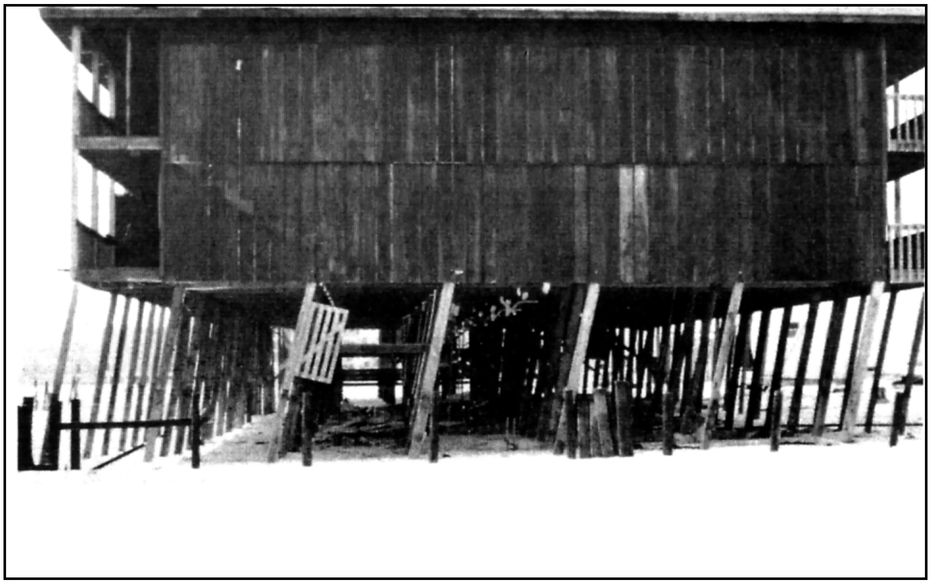


Figure 2-19
Hurricane Frederic (1979). Effects of wind and water forces on unbraced pile foundation.

Approximately 73 percent of front-row buildings were destroyed, while only 34 percent of second- and third-row buildings were destroyed. The destruction of non-elevated buildings was predictable; however, large numbers of elevated houses built to the BFE enforced at that time were also destroyed. Analyses confirmed that much of the damage to houses elevated to the BFE occurred because the BFE was based on the stillwater level only. It was after Hurricane Frederic that FEMA began to include wave heights in its determination of BFEs in coastal flood hazard areas.

The conclusion of the 1980 FEMA study was supported by studies by Rogers (1990, 1991), which assessed damage to buildings constructed in Gulf Shores before and after 1972, when the community adopted minimum floor elevation standards based on its first NFIP flood hazard map. In addition to showing that the adoption of the 1972 standards helped reduce damage, the 1991 study showed the value of incorporating wave heights into BFEs and noted the further need to account for the effects of erosion and overwash.

CROSS-REFERENCE

Section 3.3.1, in Chapter 3 of this manual, explains how wave heights are considered in FEMA's determination of BFEs in coastal areas.

1983, August 17–18 – Hurricane Alicia, Galveston and Houston, Texas. Hurricane Alicia came ashore near Galveston, Texas, during the night of August 17-18, 1983. It was the first tropical cyclone of the 1983 Atlantic hurricane season and the first hurricane to strike the continental United States since Hurricane Allen made landfall in August 1980. After Hurricane Agnes, which caused inland flooding over a large part of the U.S. east coast, Alicia was the second most costly storm to strike the United States at that time. A study by the National Academy of Sciences (NAS 1984) states that property damage resulting from Alicia was exceeded only by that of Hurricane Frederic. Wind damage was extensive throughout the Galveston–Houston area, and rain and storm surge caused flood damage in areas along the Gulf of Mexico and Galveston Bay.

The NAS report (1984) states that most of the property damage resulting from Alicia was caused by high winds. Overall, more than 2,000 homes and apartments were destroyed and over 16,000 other homes and apartments were damaged. The report noted the following concerning damage to residential buildings:

- Single-family and multi-family dwellings, and other small buildings that are usually not engineered, experienced the heaviest overall damage.
- Most of the damage to wood-frame houses could easily be traced to inadequate fastening of roof components, poor anchorage of roof systems to wall frames, poor connections of wall studs to the plates, and poor connections of sill plates to foundations. In houses that were destroyed, hurricane clips were usually either installed improperly or not used at all.
- Single-family dwellings near the water were extensively damaged by a combination of wind, surge, and wave action. Some were washed off their foundations and transported inland by the storm surge and waves.
- The performance of elevated wood-frame buildings along the coast can be significantly improved through the following actions:
    a) ensuring that pilings are properly embedded
    b) providing a continuous load path with the least possible number of weak links
    c) constructing any grade-level enclosures with breakaway walls
    d) protecting openings in the building envelope with storm shutters
    e) adequately elevating air-conditioning compressors

1995, October 4 – Hurricane Opal, Florida Panhandle. Hurricane Opal was one of the more damaging hurricanes to ever affect Florida. In fact, the state concluded that more coastal buildings were damaged or destroyed by the effects of flooding and erosion during Opal than in all other coastal storms affecting Florida in the previous 20 years combined. Erosion and structural damage were exacerbated by the previous effects of Hurricane Erin, which hit the same area just 1 month earlier.

The Florida Bureau of Beaches and Coastal Systems (FBBCS) conducted a post-storm survey to assess structural damage to major residential and commercial buildings constructed seaward of the Florida Coastal Construction Control Line (CCCL). The survey revealed that out of 1,942 existing buildings, 651 had sustained some amount of structural damage.

None of these damaged buildings had been permitted by FBBCS (all pre-dated CCCL permit requirements). Among the 576 buildings for which FBBCS had issued permits, only 2 sustained structural damage as a result of Opal (FBBCS 1996), and those 2 did not meet the state's currently implemented standards.

A FEMA Building Performance Assessment Team evaluated damage (FEMA 1996) in the affected area and concluded the following:

- Damaged buildings generally fell into one of the following four categories:
    a) pre-FIRM buildings founded on slabs or shallow footings and located in mapped V zones
    b) post-FIRM buildings outside mapped V zones and on slab or shallow footing foundations, but subject to high-velocity wave action, high-velocity flows, erosion, impact by floodborne debris, and/or overwash
    c) poorly designed or constructed post-FIRM elevated buildings
    d) pre-FIRM and post-FIRM buildings dependent on failed seawalls or bulkheads for protection and foundation support
- Oceanfront foundations were exposed to 3–7 feet of vertical erosion in many locations (see Figure 2-20). Lack of foundation embedment, especially in the case of older elevated buildings, was a significant contributor to building loss.

Figure 2-20
Hurricane Opal (1995), Bay County, Florida. Building damage from erosion and undermining.

- Two communities enforced freeboard and V zone foundation requirements in coastal A zones. In these communities, the performance of buildings subject to these requirements was excellent.
- State-mandated elevation, foundation, and construction requirements seaward of the Coastal Construction Control Line exceeded minimum NFIP requirements and undoubtedly reduced storm damage.

The National Association of Home Builders (NAHB) Research Center also conducted a survey of damaged houses (1996). In general, the survey revealed that newer wood-frame construction built to varying degrees of compliance with the requirements of the *Standard for Hurricane Resistant Residential Construction SSTD 10-93* (SBCCI 1993), or similar construction requirements, performed very well overall, with virtually no wind damage. In addition, the Research Center found that even older houses not on the immediate coastline performed well, partly because the generally wooded terrain helped shield these houses from the wind.

1998, September 28 – Hurricane Georges, Mississippi, Alabama, and Florida. Hurricane Georges made landfall in the Ocean Springs/Biloxi, Mississippi, area. Over the next 30 hours, the storm moved slowly north and east, causing heavy damage along the Gulf of Mexico coast. According to data from NWS reports, the maximum sustained winds ranged from 46 mph at Pensacola, Florida, to as high as 91 mph, with peak gusts up to 107 mph at Sombrero Key in the Florida Keys. Storm surges over the area ranged from more than 5 feet in Pensacola to 9 feet in Pascagoula, Mississippi. The total rainfall in the affected area ranged from 8 to 38 inches.

A Building Performance Assessment Team (BPAT) deployed by FEMA conducted aerial and ground investigations of building performance in Gulf coast areas from Pensacola Beach, Florida, to Gulfport, Mississippi, and inland areas flooded by major rivers and streams. In coastal areas, the BPAT evaluated primarily one- and two-family, one- to three-story wood-frame buildings elevated on pilings, although a few slab-on-grade buildings were also inspected.

The findings of the BPAT (FEMA 1999a) are summarized below:

- Engineered buildings performed well when constructed in accordance with current building codes, such as the Standard Building Code (SBC), local floodplain management requirements compliant with the NFIP regulations, and additional state and local standards.
- Communities that recognized and required that buildings be designed and constructed for the actual hazards present in the area suffered less damage.

- Specialized building materials such as siding and roof shingles designed for higher wind speeds performed well.
- Publicly financed flood mitigation programs and planning activities clearly had a positive effect on the communities in which they were implemented.

The BPAT concluded that several factors contributed to the building damage observed in the Gulf coast area, including the following:

- inadequate pile embedment depths on coastal structures (see Figure 2-21)
- inadequately elevated and inadequately protected utility systems
- inadequate designs for frangible concrete slabs below elevated buildings in coastal areas subject to wave action
- impacts from waterborne debris on coastal buildings
- lack of consideration of erosion and scour in the siting of coastal buildings
- corrosion of metal fasteners (e.g., hurricane straps) on coastal buildings

Figure 2-21
Hurricane Georges (1998), Dauphin Island, Alabama. As a result of erosion, scour, and inadequate pile embedment, the house on the right was washed off its foundation and into the house on the left.

2.2.4 Pacific Coast

1964, March 27 – Alaska Tsunami. This tsunami, generated by the 1964 Good Friday earthquake, affected parts of Washington, Oregon, California, and Hawaii; however, the most severe effects were near the earthquake epicenter in Prince William Sound, southeast of Anchorage, Alaska (Wilson and Tørum 1968). The tsunami flooded entire towns and caused extensive damage to waterfront and upland buildings (see Figure 2-22). Tsunami runup reached approximately 20 feet above sea level in places, despite the fact that the main tsunami struck near the time of low tide. Also, liquefaction of coastal bluffs in Anchorage resulted in the loss of buildings.

Figure 2-22
1964 Good Friday earthquake. Damage in Kodiak City, Alaska, caused by the tsunami of the 1964 Alaskan earthquake (from Wilson and Tørum 1968).

The 1968 report (p. 379) provides recommendations for land and waterfront buildings, including the following:

- Buildings on exposed land should have deep foundations of reinforced concrete or of the beam and raft type, to resist scour and undermining.
- Buildings should be oriented, if possible, to expose their shorter sides to potential wave inundation.
- Reinforced concrete or steel-frame buildings with shear walls are desirable.
- Wood-frame buildings should be located in the lee of more substantial buildings.
- Wood-frame buildings should be well-secured to their foundations, and have corner bracing at ceiling level.
- Wood-frame buildings in very exposed, low-lying areas should be designed so that the ground floor area may be considered expendable, because wetting damage would be inevitable. Elevated “stilt” designs of aesthetic quality should be considered.
- Tree screening should be considered as a buffer zone against the sea and for its aesthetic value.

1982-83 – Winter Coastal Storms, California, Oregon, and Washington. A series of El Niño-driven coastal storms caused widespread and significant damage to beaches, cliffs, and buildings along the coast between Baja California and Washington. These storms were responsible for more coastal erosion and property damage from wave action than had occurred since the winter of 1940-41 (Kuhn and Shepard 1991). One assessment of winter storm damage in the Malibu, California, area (Denison and Robertson 1985) found the following storm effects:

- Many beaches were stripped of their sand, resulting in 8–12 feet of vertical erosion.
- Bulkheads failed when scour exceeded the depth of embedment and backfill was lost.
- Many oceanfront houses were damaged or destroyed, particularly older houses.
- Sewage disposal systems that relied on sand for effluent filtration were damaged or destroyed.
- Battering by floating and wave-driven debris (pilings and timbers from damaged piers, bulkheads, and houses) caused further damage to coastal development.

CROSS-REFERENCE

Chapter 7 and Appendix G discuss the identification of hazard zones in coastal areas.

A 1985 conference on coastal erosion, storm effects, siting, and construction practices was organized largely as a result of the 1982-83 storms. The proceedings (McGrath 1985) highlights many of the issues and problems associated with construction along California's coast:

- the need for high-quality data on coastal erosion and storm effects
- the vulnerability of houses constructed atop coastal bluffs, out of mapped floodplains, but subject to destruction by erosion or collapse of the bluffs
- the benefits, adverse impacts, and costs associated with various forms of bluff stabilization, erosion control, and beach nourishment
- the need for rational siting standards in coastal areas subject to erosion, wave effects, or bluff collapse

January 1988 – Winter Coastal Storm, Southern California. This storm was unusual because of its rapid development, small size, intensity, and track. While most winter storms on the Pacific coast are regional in scale and affect several states, damage from this storm was largely confined to southern California. Damage to harbor breakwaters, shore protection structures, oceanfront buildings, and infrastructure were severe, as a result of the extreme waves associated with this storm. One study (Seymour 1989) concluded that wave heights for the January 1988 storm were the highest recorded and would have a recurrence interval of at least 100-200 years.

1997-98 – Winter Coastal Storms, California and Oregon. Another series of severe El Niño-driven coastal storms battered the Pacific coast. The distinguishing feature of the 1997-98 event was rainfall. The California

Coastal Commission (1998) reported widespread soil saturation, which resulted in thousands of incidents of debris flows, landslides, and bluff collapse (see Figure 2-23).

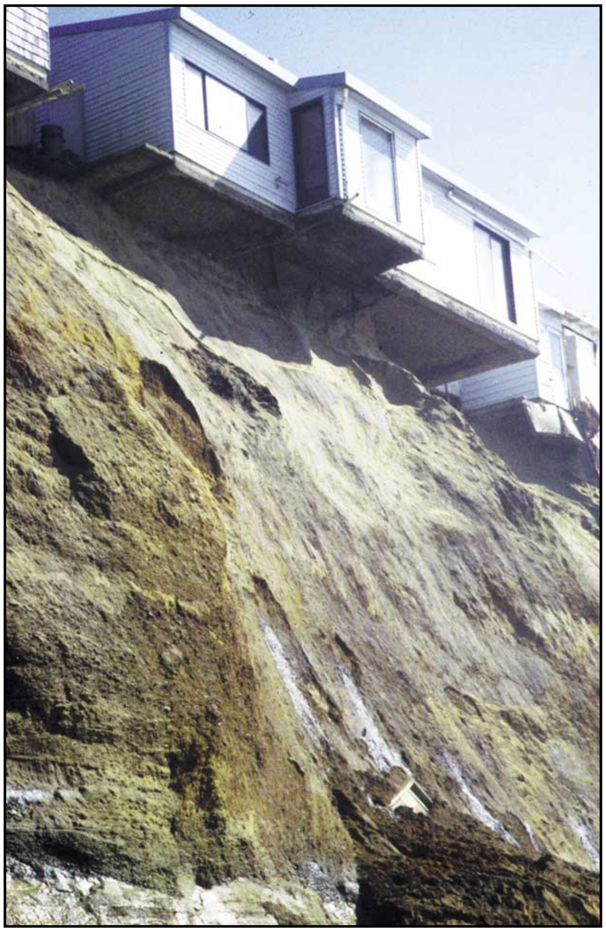
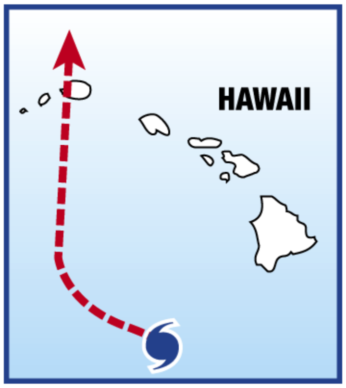


Figure 2-23
Winter coastal storms, California and Oregon (1997–1998). House in Pacifica, California, undermined by bluff erosion. Photograph by Lesley Ewing, courtesy of the California Coastal Commission.

2.2.5 Hawaii and U. S. Pacific Territories



1992, September 11 – Hurricane Iniki, Kauai County, Hawaii. Hurricane Iniki was the strongest hurricane to affect the Hawaiian Islands in recent memory—it was stronger than Hurricane Iwa (1992) and Hurricane Dot (1959) and caused significant flood and wave damage to buildings near the shoreline. Before Iniki, BFEs in Kauai County had been established based on tsunami effects only; following the storm, BFEs were reset based on both tsunami and hurricane flood effects. FEMA's Building Performance Assessment Team (BPAT) for Hurricane Iniki, in its report (FEMA 1993b), concluded that the following factors contributed to flood damage :

- buildings constructed at-grade
- inadequately elevated buildings
- inadequate structural connections

- inadequate connections between buildings and their pier or column foundations, which allowed flood waters to literally "float" buildings off their foundations (see Figure 2-24)
- embedment of foundations in unconsolidated sediments (see Figure 2-25)
- improper connection of foundations to underlying shallow rock
- impact of floodborne debris, including lava rock and parts of destroyed structures (Most of the lava rock debris originated from rock landscaping and privacy walls, which were common in the area.)

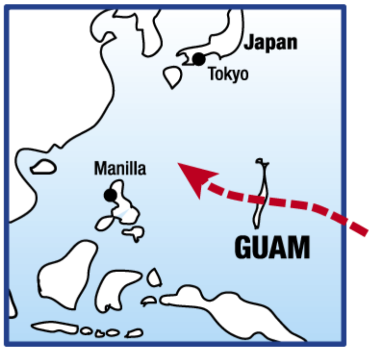
Figure 2-24
Hurricane Iniki (1992). Non-elevated house at Poipu Beach that floated off its foundation and was pinned against another house and destroyed by waves.

Figure 2-25
Hurricane Iniki (1992). Undermining of shallow footings supporting columns at Poipu Beach due to lack of sufficient embedment below erosion level.

The BPAT concluded that the following factors contributed to the observed wind damage:

- inadequately attached roof sheathing and roof coverings
- roof overhangs greater than 3 feet
- inadequately designed roofs and roof-to-wall connections
- unprotected windows and doors
- poor quality of construction
- deterioration of building components, principally due to wood rot and corrosion of metals
- wind speedup effects due to changes in topography

The BPAT concluded that properly elevated and constructed buildings sustained far less damage than buildings that were inadequately elevated or constructed.



1997, December 16 – Typhoon Paka, Guam. In January 1998, FEMA deployed a Hazard Mitigation Technical Assistance Program (HMTAP) team to Guam to evaluate building performance and damage to electric power distribution systems. In its report (FEMA 1998), the team noted that damage to wood-frame buildings was substantial, but that many buildings were built with reinforced masonry or reinforced concrete and survived the storm with minimal damage (see Figure 2-26). Many of the roof systems were flat and many were covered with a "painted-on" coating that also survived the storm with almost no damage. At the time of the storm, Guam used the 1994 Uniform Building Code (ICBO 1994) but has adopted a local amendment specifying a design wind speed of 155 mph (fastest-mile basis).

Figure 2-26
Typhoon Paka (1997). Although damaged by the storm, the concrete house in the upper part of the photograph survived, while the wood-frame house next to it was destroyed.

2.2.6 Great Lakes

1940, November 11 – Armistice Day Storm, Lake Michigan. On the afternoon of November 11, high winds moved quickly from the southwest into the area around Ludington, Michigan, on the eastern shoreline of Lake Michigan. Heavy rains accompanied the winds and later changed to snow. The winds, which reached speeds as high as 75 mph, overturned small buildings, tore the roofs from others, toppled brick walls, uprooted trees, and downed hundreds of telephone and power lines throughout the surrounding areas of Mason County.

1951, November 7 – Storm on Lake Michigan. After 20 years of lower-than-average levels, the water level on Lake Michigan in November 1951 was slightly above average. The November 7 storm caused extensive erosion along the southeast shore of the lake, undermining houses and roads (see Figure 2-27). Damage observed as a result of this storm is consistent with the concept of Great Lakes shoreline erosion as a slow, cumulative process, driven by lakebed erosion, high water levels, and storms.

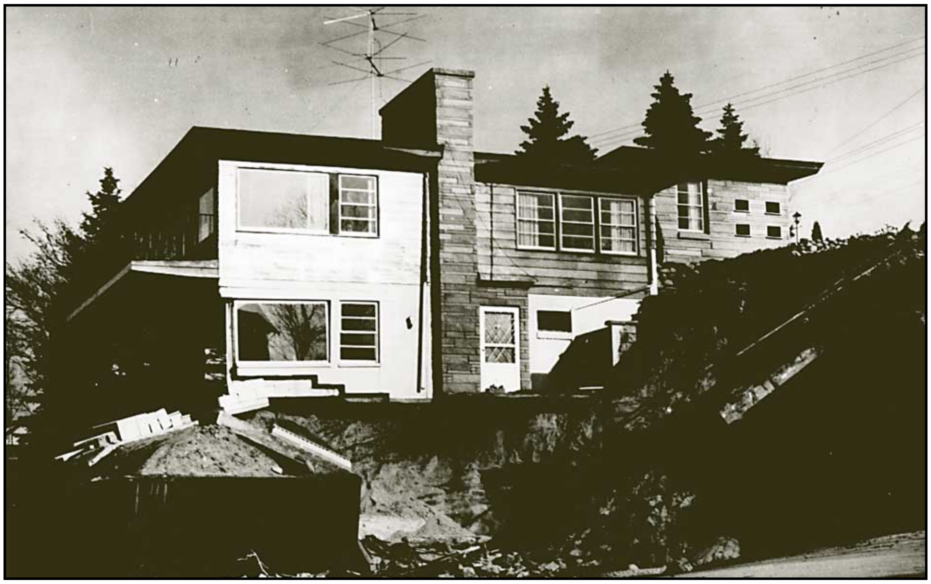


Figure 2-27
House on southeastern shoreline of Lake Michigan undermined by erosion during storm of November 1951. Photograph courtesy of USACE, Chicago District.

1973, April 9 – Northeaster, Lake Michigan. This storm caused flooding 4 feet deep in downtown Green Bay, Wisconsin. Flood waters reached the elevation of the 500-year flood as strong winds blowing the length of the bay piled up a storm surge on already high lake levels. Erosion damage occurred on the open coast of the lake.

1975, November 9 and 10 – Storm on the western Great Lakes. This storm, one of the worst to occur on Lake Superior since the 1940's, caused the sinking of the 729-foot-long ore carrier *Edmund Fitzgerald* in eastern Lake Superior, with the loss of all 29 of its crew. The storm severely undermined the harbor breakwater at Bayfield, Wisconsin, requiring its replacement the following year. Bayfield is relatively sheltered by several of the Apostle Islands. A portion of the Superior Entry rubblemound jetty was destroyed at Duluth-Superior in the eastern end of Lake Superior and had to be repaired. Storm waves on the open lake were estimated by mariners to range from 20 to 40 feet in height.

1985, March – Storms on the Great Lakes. As lake levels were rising toward the new record levels that would be set in 1986, the Town of Hamburg, New York, south of Buffalo, New York, was flooded by a damaging 8-foot storm surge from Lake Erie, which was driven by strong westerly winds. In this same month, properties along the lower sand bank portions of Wisconsin's Lake Michigan shore experienced 10–50 feet of rapid shoreline recession in each of several weekend storms, which suddenly placed lakeside homes in peril. Some houses had to be quickly relocated.

1987, February. This storm occurred during a period of record high lake levels. Sustained northerly wind speeds were estimated to be in excess of 50 mph, and significant deepwater wave heights in the southern portion of the lake were estimated to be greater than 21 feet (USACE 1989).

1986, 1996, 1997 – Sometimes, stalled storm systems bring extremely heavy precipitation to local coastal areas, where massive property damage results from flooding, bluff and ravine slope erosion from storm runoff, and bluff destabilization from elevated groundwater. The southeastern Wisconsin coast of Lake Michigan had three rainfall events in excess of the 500-year precipitation event within 11 recent years: August 6, 1986 (Milwaukee, Wisconsin); June 16-18, 1996 (Port Washington, Wisconsin); and June 20-21, 1997 (northern Milwaukee County, including the City of Milwaukee) (SWRPC 1997). Massive property damage from flooding was reported in all three events, and Port Washington suffered severe coastal and ravine erosion during the 1996 event.

The Chicago District of the U. S. Army Corps of Engineers, using its Great Lakes Storm Damage Reporting System (GLSDRS), has estimated the total damage for storm-affected shoreline areas of the Great Lakes in 1996 and 1997 to be $1,341,000 and $2,900,000, respectively (USACE 1997, 1998). These amounts include damage to buildings, contents, vehicles, landscaping, shore protection, docks, and boats.

Figure 2-28
August 1988. Erosion along the Lake Michigan shoreline at Holland, Michigan, resulting from high lake levels and storm activity (photo courtesy of Mark Crowell).

2.3 Lessons Learned

Although flood events and physiographic features vary throughout the coastal areas of the United States, post-event damage reports show that the nature and extent of damage caused by coastal flood events are remarkably similar. Moreover, review of these reports shows that the types of damage experienced today are, in many ways, similar to those experienced decades ago. It is clear that although we have improved many aspects of coastal construction over the years, we make many of the same mistakes over and over.

The conclusions of post-event assessments can be classified according to those factors that contribute to both building damage and successful building performance: hazard identification, siting, design, construction, and maintenance. Reduction of building damages in coastal areas will require attention to these conclusions and coordination between owners, designers, builders, and local officials.

NOTE

Although there is no statistical basis for the conclusions presented in this section, they are based on numerous post-event damage assessments, which serve as a valuable source of information on building performance and coastal development practices.

2.3.1 Hazard Identification

- Flood damage can result from the effects of **short- and long-term increases in water levels** (storm surge, tsunami, seiche, sea-level rise); wave action; high-velocity flows; erosion; and debris. Addressing all potential flood hazards at a site will help reduce the likelihood of building damage or loss.

CROSS-REFERENCE

Chapter 7 of this manual discusses the identification of coastal hazards and their effects on coastal buildings.

CROSS-REFERENCE

See Figure 5-5, in Chapter 5, for an example of the effects of multiple storms.

WARNING

FIRMs do not account for future effects of long-term erosion. Users are cautioned that all mapped flood hazard zones (V, A, and X) in areas subject to long-term erosion will likely underestimate the extent and magnitude of actual flood hazards that a coastal building will experience over its lifetime.

CROSS-REFERENCE

Sections 1.4 and 3.3 of this manual explain the concept of a coastal A zone.

- Failure to consider the **effects of multiple storms or flood events** may lead to an underestimation of flood hazards in coastal areas; coastal buildings left intact by one storm may be vulnerable to damage or destruction by a second storm.

- **Long-term erosion** can increase coastal flood hazards through time, causing loss of protective beaches, dunes, and bluffs, and soils supporting building foundations. Failure to account for long-term erosion is one of the more common errors made by those siting and designing coastal residential buildings.

- Flood hazards in areas mapped as A zones on coastal FIRMs can be much greater than flood hazards in riverine A zones. There are two reasons for this situation:

    1. Waves 2–3 feet high (i.e., too small for an area to be classified as a V zone, but still capable of causing structural damage and erosion) will occur during base flood conditions in many coastal A zones.

    2. Aging FIRMs may fail to keep pace with changing site conditions (e.g., long-term erosion, loss of dunes during previous storms) and revised flood hazard mapping procedures.

  Therefore, minimum A-zone foundation and elevation requirements should not be assumed adequate to resist coastal flood forces without a review of actual flood hazards. The concept of a "**coastal A Zone**" with elevation and foundation requirements closer to those of V zones should be considered.

- Failure to consider the **effects of topography** (and changes in topography, e.g., bluff erosion) on **wind speeds** can lead to underestimation of wind speeds that will be experienced during the design event. Siting buildings on high bluffs or near high-relief topography requires special attention by the designer.

- In coastal bluff areas, consideration of the potential effects of surface and subsurface drainage, removal of vegetation, and site development activities can help reduce the likelihood of problems resulting from **slope stability hazards and landslides**.

- **Drainage from septic systems** on coastal land can destabilize coastal bluffs and banks, accelerate erosion, and increase the risk of damage and loss to coastal buildings.

- Vertical cracks in the soils of some cohesive bluffs cause a rapid rise of **groundwater in the bluffs** during extremely heavy and prolonged precipitation events and rapidly decrease the stability of such bluffs.

- Some coastal areas are also susceptible to seismic hazards; although the likelihood of flood and seismic hazards acting simultaneously is small, each hazard should be identified carefully and factored into siting, design, and construction practices.

2.3.2 Siting

- **Building close to the shoreline** is a common, but possibly poor, siting practice: it may render a building more vulnerable to wave, flood, and erosion effects; may remove any margin of safety against multiple storms or erosion events; and may require moving, protecting, or demolishing the building if flood hazards increase over time.
- In coastal areas subject to long-term or episodic erosion, poor siting often results in otherwise well-built **elevated buildings standing on the active beach**. While a structural success, such buildings are generally uninhabitable (because of the loss of utilities and access). This situation can also lead to conflicts over beach use and increase pressure to armor or renourish beaches (controversial and expensive measures).
- **Building close to other structures** may increase the potential for damage from flood, wind, debris, and erosion hazards. Of particular concern is the siting of homes or other small buildings adjacent to large, engineered high-rise structures—the larger structures can redirect and concentrate flood, wave, and wind forces, and have been observed to increase flood and wind forces as well as scour and erosion.
- Depending on erosion or flood protection structures often leads to building damage or destruction. Seawalls, revetments, berms, and other structures may not afford the required protection during a design event and may themselves be vulnerable as a result of erosion and scour or other prior storm impacts. **Siting too close to protective structures** may preclude or make difficult any maintenance of the protective structure.
- **Siting buildings on the tops of erodible dunes and bluffs** renders those buildings vulnerable to damage caused by the undermining of foundations and the loss of supporting soil around vertical foundation members.
- **Siting buildings on the downdrift shoreline** of a stabilized tidal inlet (an inlet whose location has been fixed by jetties) often places the buildings in an area subject to increased erosion rates.
- **Siting buildings near unstabilized tidal inlets** or in areas subject to large-scale shoreline fluctuations may result in increased vulnerability to even minor storms or erosion events.

CROSS-REFERENCE

Chapter 8 of this manual discusses siting considerations, siting practices to avoid, and recommended alternatives.

CROSS-REFERENCE

Figures 4-1, 4-2, and 7-28, in Chapters 4 and 7 of this manual, show the consequences of poor siting.

CROSS-REFERENCE

Figures 7-38 and 7-39, in Chapter 7 of this manual, show the consequences of siting buildings on the tops of erodible bluffs.

- Siting along shorelines protected against wave attack by barrier islands or other land masses does not guarantee protection against flooding. In fact, **storm surge elevations along low-lying shorelines in embayments** are often higher than storm surge elevations on open coast shorelines.

CROSS-REFERENCE

Chapter 12 of this manual covers the design of coastal buildings.

2.3.3 Design

- Use of **shallow spread footing and slab foundations** in areas subject to wave impact and/or erosion can result in building collapse, even during minor flood or erosion events. Because of the potential for undermining by erosion and scour, shallow spread footing and slab foundations may not be appropriate for some coastal A zones and some coastal bluff areas outside the mapped floodplain.
- In areas subject to wave impact and/or erosion, the use of **continuous perimeter wall foundations**, such as crawlspace foundations, (especially those constructed of unreinforced masonry) may result in building damage, collapse, or total loss.
- Inadequate depth of foundation members (e.g., pilings not embedded deeply enough, shallow footings supporting masonry and concrete walls and columns) is a common cause of failure in elevated 1- to 4-family residential buildings.
- Elevating a building sufficiently will help protect the superstructure from damaging wave forces. **Designs should incorporate freeboard** above the required elevation of the lowest floor or bottom of lowest horizontal member.
- Failure to **use corrosion-resistant structural connectors** (e.g., wooden connectors, galvanized connectors made of heavier gauge metal or with thicker galvanizing, stainless steel connectors) can compromise structural integrity and may lead to building failures under less than design conditions.
- **Corrosion of metal building components** is accelerated by salt spray and breaking waves. Nails, screws, sheet-metal connector straps, and truss plates are the most likely to be threatened by corrosion.
- Failure to provide a **continuous load path** using adequate connections between all parts of the building, from the roof to the foundation, may lead to structural failure.
- **Multi-story decks/roofs** supported by inadequately embedded vertical members can lead to major structural damage, even during minor flood and erosion events. Either roof overhangs should be designed to remain intact without vertical supports, or supports

should be designed to the same standards as the main foundation. Decks must be designed to withstand all design loads or should be designed so that they do not cause damage to the main building when they fail.

- Failure to adequately connect **porch roofs** and to limit the size of **roof overhangs** can lead to extensive damage to the building envelope.
- Many coastal communities have building height restrictions that, when coupled with building owner's desires to maximize building size and area, encourage the use of **low-slope roofs**. These roofs can be more susceptible to wind damage and water penetration problems.
- Roof designs that incorporate gable ends (especially **unbraced gable ends**) and **wide overhangs** are susceptible to failure unless adequately designed and constructed for the expected loads. Alternative designs that are more resistant to wind effects should be used in coastal areas.
- Many commonly used residential roofing techniques, systems, and materials are susceptible to damage from wind and windborne debris. Designs should pay special attention to the **selection and attachment of roof sheathing and roof coverings** in coastal areas.
- **Protection of the entire building envelope** is necessary in high-wind areas. Therefore, proper specification of windows, doors, and their attachment to the structural frame is essential.
- **Protecting openings** with temporary or permanent storm shutters and the use of impact-resistant (e.g., laminated) glass will help protect the building envelope and reduce damage caused by wind, windborne debris, and rainfall penetration.
- Designs should **maximize the use of lattice and screening** below the BFE and minimize the use of breakaway wall enclosures in V zones and solid wall enclosures in A zones. Post-construction conversion of enclosures to habitable space remains a common violation of floodplain management requirements and is difficult for communities and states to control.
- The **design and placement of swimming pools** can affect the performance of adjacent buildings. Pools should not be structurally attached to buildings, because an attached pool can transfer flood loads to the building. Building foundation designs should also account for increased flow velocities, wave ramping, wave deflection, and scour that can result from the redirection of flow by an adjacent pool.

CROSS-REFERENCE

Chapter 13 of this manual covers the construction of coastal buildings.

2.3.4 Construction

- **Poorly made structural connections**, particularly in wood-frame and masonry structures, (e.g., pile/pier/column to beam, joist to beam) have been observed to cause the failure of residential structures throughout the coastal areas of the United States.
- **Connections must be made with the appropriate fastener** for the design structural capacity to be attained. For example, post-event investigations have revealed many inadequate connections (e.g., made with the wrong size nails) that either failed during the event or could have failed if the design loads had been realized at the connection.
- **Nail and staple guns**, which are frequently used to speed construction, have disadvantages that can lead to connections with reduced capacity. These guns can easily overdrive nails or staples, or drive them at an angle. In addition, it is often difficult for the nail gun operator to determine whether a nail has penetrated an unexposed wood member as intended, such as a rafter or truss below roof sheathing.
- Failure to achieve the **pile or foundation embedment** specified by building plans or local/state requirements will render an otherwise properly-constructed building vulnerable to flood, erosion, and scour damage.
- **Improperly constructed breakaway walls** (e.g., improperly fastened wall panels, panels constructed immediately seaward of foundation cross-bracing) can cause preventable damage to the main structure. Lack of knowledge or inattention by contractors can cause unnecessary damage.
- **Improperly installed utility system components** (e.g., plumbing and electrical components attached to breakaway walls or on the waterward side of vertical foundation members, unelevated or insufficiently elevated heat pumps/air conditioning compressors and ductwork) will not only fail during a flood event, they can also cause damage to the main structure that otherwise might not have occurred.
- **Bracing and fastening roofs and walls** can help prevent building envelope failures in high-wind events.
- Lack of, or inadequate, connections between shingles and roof sheathing and between sheathing and roof framing (e.g., nails that fail to penetrate roof truss members or rafters) can cause **roof failures** and subsequent building failures.

- Communities often have **insufficient resources to inspect buildings** frequently during construction. Although contractors are responsible for following plans and satisfying code requirements, infrequent inspections may result in failure to find and remedy construction deficiencies.

2.3.5 Maintenance

- **Repairing and replacing structural elements**, connectors, and building envelope components that have deteriorated over time, because of decay or corrosion, will help maintain the building's resistance to natural hazards. Maintenance of building components in coastal areas should be a constant and ongoing process. The ultimate costs of deferred maintenance in coastal areas can be high when natural disasters strike.
- **Failure to inspect and repair damage** caused by a wind, flood, erosion, or other event will make the building even more vulnerable during the next event.
- **Failure to maintain erosion control or coastal flood protection structures** will lead to increased vulnerability of those structures and the buildings behind them.

CROSS-REFERENCE

Chapter 14 of this manual covers the maintenance of coastal buildings.

2.4 References

California Coastal Commission. 1998. *Coastal Impacts of the 1997-98 El Nino and Predictions for La Nina*. August 28 Memorandum to Interested Parties.

Davis, R. E.; R. Dolan. 1991. "The 'All Hallows Eve' Coastal Storm October 1991." *Journal of Coastal Research*. Vol. 8, No. 4, pp. 978-983.

Denison, F. E.; H. S. Robertson. 1985. "1982-1983 Winter Storms Damage, Malibu Coast." *California Geology*. September 1985.

Dolan, R.; R. E. Davis. 1992. "Rating Northeasters." *Mariners Weather Log*. Vol. 36, No. 1, pp. 4-11.

Eefting, T. 1927. "Structural Lessons of the South Florida Hurricane." *Florida Engineer and Contractor*. September. pp. 162-170.

Federal Emergency Management Agency. 1980. *Elevating to the Wave Crest Level — A Benefit:Cost Analysis*. FIA-6.

Federal Emergency Management Agency. 1992. *Building Performance Assessment Team, Field Trip and Assessment within the States of Maryland and Delaware in Response to a Nor'easter Coastal Storm on January 4, 1992*. Final Report. March 4.

Federal Emergency Management Agency. 1993a. *Building Performance: Hurricane Andrew in Florida, Observations, Recommendations and Technical Guidance*. FIA-22.

Federal Emergency Management Agency. 1993b. *Building Performance: Hurricane Iniki in Hawaii, Observations, Recommendations and Technical Guidance*. FIA-23.

Federal Emergency Management Agency. 1996. *Hurricane Opal in Florida, A Building Performance Assessment*. FEMA-281.

Federal Emergency Management Agency. 1997. *Building Performance Assessment: Hurricane Fran in North Carolina, Observations, Recommendations and Technical Guidance*. FEMA-290.

Federal Emergency Management Agency. 1998. *Typhoon Paka: Observations and Recommendations on Building Performance and Electrical Power Distribution Systems, Guam, USA*. FEMA-1193-DR-GU. March.

Federal Emergency Management Agency. 1999a. *Hurricane Georges… In the Gulf Coast – Observations, Recommendations, and Technical Guidance*. FEMA 338.

Federal Emergency Management Agency. 1999b. *Hurricane Georges in Puerto Rico – Observations, Recommendations, and Technical Guidance*. FEMA 339.

Florida Bureau of Beaches and Coastal Systems. 1996. *Hurricane Opal, Executive Summary of a Report on Structural Damage and Beach and Dune Erosion Along the Panhandle Coast of Florida*.

Hayes, M. O. 1967. "Hurricanes as Geological Agents: "Case Studies of Hurricanes Carla, 1961, and Cindy, 1963." *Bureau of Economic Geology Report of Investigation No. 61*. Austin, TX: University of Texas.

International Conference of Building Officials. 1994. *Uniform Building Code*. Vol. 1-3.

Kuhn, G. G.; F. P. Shepard. 1991. *Sea Cliffs, Beaches and Coastal Valleys of San Diego County: Some Amazing Histories and Some Horrifying Implications*. University of California Press

McGrath, J., ed. 1985. "California's Battered Coast." Proceedings from a February 6-8, 1985, Conference on Coastal Erosion. California Coastal Commission.

Minsinger, W.E. 1988. *The 1938 Hurricane, An Historical and Pictorial Summary*. Blue Hill Meteorological Observatory, East Milton, MA. Greenhills Books, Randolph Center, VT.

National Academy of Sciences, National Research Council, Commission on Engineering and Technical Systems. 1984. *Hurricane Alicia, Galveston and Houston, Texas, August 17-18, 1983*.

National Association of Home Builders Research Center. 1996. *Assessment of Damage to Homes Caused by Hurricane Opal*, Final Report. Prepared for the Florida State Home Builders Association. January.

National Oceanic and Atmospheric Administration. 1996. *North Atlantic Hurricane Track Data, 1886-1996*.

National Oceanic and Atmospheric Administration. 1997. *The Deadliest, Costliest, and Most Intense United States Hurricanes of this Century*. NOAA Technical Memorandum NWS TPC-1. February update.

National Roofing Contractors Association. 1996. *Hurricane Marilyn, Photo Report of Roof Performance*. Prepared for the Federal Emergency Management Agency. March.

New Jersey Department of Environmental Protection, Division of Coastal Resources and Division of Water Resources. 1986. *Hazard Mitigation Plan (Section 406 Plan)*. Trenton, NJ. Revised.

Rogers, S. M. 1990. "Designing for Storm and Wave Damage in Coastal Buildings." *Proceedings of the 22nd International Conference on Coastal Engineering, July 2-6, 1990*. Delft, The Netherlands. B. L. Edge, ed. Vol. 3, pp. 2908 – 2921. New York: American Society of Civil Engineers.

Rogers, S. M. 1991. "Flood Insurance Construction Standards: Can They Work on the Coast?" *Proceedings of the 7th Symposium on Coastal and Ocean Management, July 8-12, 1991*. Long Beach, California. O. T. Magoon et al., ed. Vol. 2, pp. 1064 – 1078.

Saffir, H. S. 1971. "Hurricane Exposes Structural Flaws." *Civil Engineering – ASCE*. pp. 54 and 55. February.

Seymour, R. J. 1989. "Wave Observations in the Storm of 17-18 January, 1988." *Shore and Beach*. Vol. 57, no. 4, October 1989, pp. 10-17.

Sherwood, G. E. 1972. "Wood Structures Can Resist Hurricanes." *Civil Engineering – ASCE*. pp. 91-94. September.

Southern Building Code Congress International, Inc. 1993. *Standard for Hurricane Resistant Residential Construction*. SSTD 10-93.

Southern Building Code Congress International, Inc. 1997. *Standard Building Code*.

Southern Forest Products Association. Undated. *How to Build Storm Resistant Structures*. New Orleans, LA.

Sparks, P. R.; S.D. Schiff; T. A. Reinhold. 1994. "Wind Damage to Envelopes of Houses and Consequent Insurance Losses." *Journal of Wind Engineering and Industrial Aerodynamics*. Vol. 53, pp. 145-155.

Southeastern Wisconsin Regional Planning Commission. 1997. Newsletter, Vol. 37, No. 3. May - June.

Thom, H. C. S.; R. D. Marshall. 1971. "Wind and Surge Damage due to Hurricane Camille." *ASCE Journal of Waterways, Harbors and Coastal Engineering Division*. May. pp. 355-363.

URS Consultants, Inc. 1986. *Post-Flood Disaster Assessment Report: Hurricane Gloria, September 27, 1985, South Shore, Long Island, NY*. Prepared for the Federal Emergency Management Agency. February.

URS Consultants, Inc. 1989. *Flood Damage Assessment Report: Sandbridge Beach, Virginia, and Nags Head, North Carolina, April 13, 1988, Northeaster*. Prepared for the Federal Emergency Management Agency. March.

URS Consultants, Inc. 1990. *Flood Damage Assessment Report: Nags Head, North Carolina, Kill Devil Hills, North Carolina, and Sandbridge Beach, Virginia, March 6-10, 1989, Northeaster.* Prepared for the Federal Emergency Management Agency. April.

URS Consultants, Inc. 1991a. *Flood Damage Assessment Report: Surfside Beach to Folly Island, South Carolina, Hurricane Hugo, September 21-22, 1989*. Volume I. Prepared for the Federal Emergency Management Agency. August.

URS Consultants, Inc. 1991b. *Follow-Up Investigation Report: Repair Efforts 9 Months After Hurricane Hugo, Surfside Beach to Folly Island, South Carolina*. Volume I. Prepared for the Federal Emergency Management Agency. August.

URS Consultants, Inc. 1991c. *Flood Damage Assessment Report: Buzzard's Bay Area, Massachusetts, Hurricane Bob, August 19, 1991*. October.

URS Consultants, Inc. 1992. *Flood Damage Assessment Report: South Shore Long Island, New York and Boston, Massachusetts Vicinity, October 1991 – Northeaster*. Draft Report. February.

U. S. Army Corps of Engineers. 1981. *Hurricane Frederic Post Disaster Report*. Mobile, AL: Mobile District.

U. S. Army Corps of Engineers. 1989. *Wave Information System Wind and Wave Hindcast for Burns Harbor, East of Chicago*. Chicago, IL: Chicago District.

U. S. Army Corps of Engineers. 1997. "Annual Summary." *Great Lakes Update*. Vol. No. 126. Detroit, MI: Detroit District. January 3.

U. S. Army Corps of Engineers. 1998. "Annual Summary." *Great Lakes Update*. Detroit, MI: Detroit District..

U.S. Department of Commerce, National Oceanographic and Atmospheric Administration. 1984. *Local Climatological Data Monthly Summary: Atlantic City, NJ.*

Walden, D. 1990. "Raising Galveston." *American Heritage of Invention and Technology*. Vol. 5, No. 3, pp. 8-18.

Wilson, B. W.; A. Tørum. 1968. *The Tsunami of the Alaskan Earthquake, 1964: Engineering Evaluation*. Technical Memorandum No. 25. U.S. Army Corps of Engineers, Coastal Engineering Research Center.

Wood, F. 1976. *The Strategic Role of Perigean Spring Tides in Nautical History and North American Coastal Flooding, 1635-1976*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Zornig, H. F.; G. E. Sherwood. 1969. *Wood Structures Survive Hurricane Camille's Winds*. USDA. Forest Service Research Paper FPL 123. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.