NCU-T-01-001 C2

Evaluating Potential Hurricane and Erosion Damage to Buildings in Coastal North Carolina

A North Carolina Sea Grant Working Paper

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UNC-SG-01-04

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Sea Grant
North Carolina

This work was supported by Grant NA86RG0036
from the National Oceanic and Atmospheric
Administration's National Sea Grant College
Program to North Carolina Sea Grant.

Evaluating Potential Hurricane and Erosion Damage

Building practices in most coastal areas of the U.S. have evolved in light of changes in regulations, local construction experience and public demand. North Carolina, in particular, has experienced a number of identifiable changes in construction practices — distinctions that can be used to improve the prediction of flood, wave and erosion damage to existing buildings. In addition, recent research at North Carolina State University has indirectly provided a more accurate threshold for building failure in waves. This report is based on observations of coastal damage following most of the severe hurricane landfalls in the U.S. since 1975 and close examination of hurricanes and smaller storms in North Carolina since 1978. Most observations address single-family houses, but larger residential and commercial structures can be similarly affected.

Wave Height Threshold for Building Damage

The National Flood Insurance Program's (NFIP) locally adopted floodplain management regulations prohibit new construction of finished or livable space below the minimum flood elevations mapped for the community. Along the coast, the highest risk areas on the maps are the V-zones — where piling foundations are required for all new buildings based on the prediction of a depth-limited 3-foot wave or larger. This minimum wave height threshold is based on a report by the Galveston District Corps of Engineers (1975), which estimated that wood-frame or brick veneer building walls would fail in larger waves.

NFIP regulations in the V-zone prohibit finishings or living space below the elevated floor. However, the regulations allow the area to be used for parking, storage or building access; and to be enclosed with solid walls, only if the walls are designed to breakaway from the piling foundation when hit by waves. Breakaway walls must be designed to fail before damaging wave forces are transferred to the foundation or to the elevated building. NFIP regulations were originally based on linear, non-breaking wave forces at peak storm surge elevations. The maximum forces were well below those required for wind design in all of the national building codes. The NFIP contracted with NCSU to develop revised guidelines for the construction of breakaway walls under piling-supported, V-zone buildings. The new design approach was based on the assumption that any wall must meet the minimum wind force requirements yet provide a reliable failure in building-threatening waves. A rising storm surge with a depth-limited breaking wave height was assumed. Tung, Kasal, Rogers & Yeh (1999) tested nail failure capacities in wet and dry conditions; conducted a theoretical wave force and wood-frame wall capacity analysis; and tested full-scale walls to failure in the wave tank at Oregon State University. The tank tests started with a wall designed for hurricane winds: 120 mph, 3-second gusts based on ASCE 7-95. The connection capacities were more than tripled during the testing. Based on the research, a technical bulletin was prepared describing breakaway wall construction details (FEMA, 1999).

The indirect result of the full-scale testing proved that standard wood-frame walls designed for very high wind speeds will fail reliably in a breaking wave exceeding 1.5 feet in height. After three or fewer 1.5-foot waves typical walls are sufficiently weakened that smaller and non-breaking waves or winds can destroy the weakened components, including the entire building if it is a bearing wall, not isolated under a piling foundation. It is therefore reasonable to assume that total failure will occur when a wood-frame building supported on a solid bearing wall or foundation is exposed to breaking waves of 1.5 feet or larger.

Piling foundations avoid the extreme impact forces applied to solid walls until the floor beams or joists are impacted. A typical piling foundation with underhouse storage or parking will allow a building to survive waves of approximately 4 feet. Wave forces generally increase with the square of the wave height, with peak velocities at the wave crest. When the larger waves begin to clip the lower portions of an elevated building, the horizontal and uplift forces are at least an order of magnitude greater than the wind design capacity of most buildings. Total destruction by larger waves occurs so quickly that it is unusual to find small, elevated buildings with partial wave damage. Rogers and Houston (1997) describe a rare example following Hurricane Hugo. The building was later determined to be a total loss. It is therefore reasonable to assume any wave impact on the beams or joists will destroy small buildings. Although less likely to collapse, larger residential and commercial buildings can expect severe damage to any low-elevation, shore parallel walls and potential damage to lower structural components, depending on the design.

Evolution of North Carolina Coastal Construction Practices

Prior to the 1950s, most coastal buildings in NC were constructed like inland buildings, with low floor elevations on slab foundations or short, unreinforced piers. Seven hurricanes impacted the state between 1953 and 1960. The Ash Wednesday Storm, an extreme northeaster, affected the state in 1962. The worst of the group was Hurricane Hazel, which made landfall on the N.C./S.C. border in 1954. Storm surges of 15 to 18 feet NGVD were reported in Brunswick County. Prior to Hazel, Oak Island had more than 350 houses near the ocean. Afterward, only five were reported to remain standing. With damage statewide in the other storms, the inland construction techniques were graphically demonstrated to be inadequate for flooding, waves and erosion, typical storm impacts near the ocean. Many of the replacement and new houses following the storms switched to piling foundations. Beginning in 1965, the use of pilings was institutionalized with the adoption of a statewide building code for residential buildings. Although initially voluntary, it included a chapter implementing hurricane-resistant construction requirements for wind, flooding and erosion on the N.C. barrier islands. It is the second oldest hurricane-resistant building code in the U.S. North Carolina is preceded only by the South Florida Building Code in the mid-1950s, following a similar binge of Florida hurricanes in the 1940s.

Prior to the N.C. code, most coastal buildings were relatively small, single-family houses. The prescriptive building code was written as a detailed "cookbook" to construct wood-frame buildings. Wind-resistant connections were universally required on the barrier islands. The closest oceanfront buildings were required to use piling foundations and to be elevated a specific height above the highest known watermark. Following the 1950s, storm surges were fresh memories and watermarks were readily available in most beach communities. The convenience of parking and storage under the piling-supported buildings convinced most oceanfront property owners to build 8 feet above grade, well above the minimum required elevations. The code required that the pilings extend to at least 8 feet below grade. In the mid 1950s and 1960s, the earliest foundations in use were 6-inch diameter, round pilings or discarded utility poles. By 1970, the availability of 16-foot square-cut wooden pilings standardized construction to 8 feet of embedment below grade, elevating the building 8 feet above grade. The required pile size was 6x6 but local practice soon switched to 8x8s. North Carolina's piling sizes and lengths are generally smaller than recommended by the NFIP or in use in other states, but the requirements have proven adequate in the flooding and waves of recent hurricanes except where affected by oceanfront erosion.

Although the general code applied statewide, the initial hurricane standards and enforcement had to be adopted locally to take effect. Most beach areas adopted the standards rather quickly compared to similarly sized inland communities. Even where not formally adopted, the methods quickly became standard construction practice. The quality of construction and local inspection varied between communities, but overall compliance can be considered very high when compared to other states. Most new buildings after 1965 appear to have met or exceeded the new standards.

An interesting side effect of the hurricane-resistant code was a nearly universal switch to piling foundations for new houses, everywhere on the barrier islands. Piling foundations were required in only the closest, oceanfront buildings. Yet statewide, almost all new houses on the islands voluntarily chose to build on piling foundations. Property owners quickly realized that if they were elevating above the historical water marks, a few extra feet of piling height would allow for underhouse parking and storage. The public perception of a beach house quickly changed from the low foundations on shallow footings of the 1950s, to piling-supported houses elevated 8 feet above grade with underhouse parking. It is obvious today that there is often little recognition of the initial storm-resistant purpose of the piling foundation. Examples can be found on every island where existing dunes are well above the predicted flood elevation, +20 to +40 feet NGVD, yet piling foundations are used to elevate an additional 8 feet higher for underhouse parking. What started as a memory of the hurricanes of the 1950s and a narrowly applied piling regulation resulted in statewide property owner demand for piling foundations as an architectural choice on the barrier islands.

The voluntary switch to pilings already has had, and will continue to have, a profound reduction in flood and wave damage in coastal North Carolina. Nationally, the only comparable shift in construction practice has occurred when local governments adopted the National Flood Insurance Program (NFIP) floor elevation requirements. However, NFIP allows wave-sensitive bearing-wall and pier foundations in coastal A-zones. Also, the desire for underhouse parking generally elevates non-oceanfront houses higher than the minimum NFIP floor levels on the NC barrier islands. The switch to elevated houses occurred 10 to 20 years earlier in North Carolina than was typically initiated by the NFIP in other states.

In 1979, the N.C. Coastal Area Management Act (CAMA) implemented the first statewide oceanfront setback line, which requires buildings to be located at least 30 times the historical erosion rate landward of the beach vegetation line. The setback prohibited construction on the smallest lots. Other regulations prohibited construction of most permanent erosion-control structures to protect buildings permitted after 1979, making piling foundations the critical design feature to survive storm-induced and long-term erosion. In 1985, the prohibition on most erosion-control structures was broadened to include all buildings, including those constructed prior to 1979. The ocean setback distance for larger commercial and multifamily residential buildings was also doubled to 60 times the historical erosion rate.

The next major change in coastal construction practice occurred in 1985, when the N.C. State Building Code Council completely revised the hurricane-resistant building code provisions. Many incremental improvements were included. The most important was an increase in the piling penetration depth for most oceanfront buildings to -5 feet NGVD or 16 feet below grade, whichever is less. Although there were few problems with pile embedment depth in non-erosion areas, it was apparent from frequent damage that the shorter depth standard of 8 feet was inadequate in oceanfront conditions. The -5 feet NGVD depth was based on retaining approximately 8 feet of penetration below the mean high water elevation. In North Carolina the mean high water (MHW) line is the fluctuating, seaward boundary that separates private ownership of higher, upland property from submerged bottom land, held in trust by the state. The 16-foot standard was a compromise for use in higher dunes, doubling the old standard.

The -5-foot standard received its first significant test in 1996 during Hurricane Fran. Most of the several hundred destroyed buildings were on the oceanfront and had been constructed on the shallower pilings. On Topsail Island, the deeper foundations were observed to have performed much better but a few were found to be leaning after only 4 to 6 feet of erosion around the pilings. Following the storm, FEMA conducted a survey of the post-1985 houses on the island (FEMA, 1997). It was determined that 205 buildings had been constructed. Five were destroyed, leaving no debris to determine the cause of damage. Eleven of the remaining houses had slightly leaning foundations. Non-destructive testing was used to determine the actual piling depth in a sample of the leaning houses. In every case tested, the piling penetration was less than required by the code. On Topsail's low ground elevations, generally the -5 feet NGVD requirement should have applied to the post-1985 houses. Assuming the leaning houses would have been stable if they had met code, the piling penetration standard proved successful in at least 97.5 percent of the post-1985 installations during design-level flooding, waves and erosion. Buildings constructed on higher dunes, where the 16-feet- below -grade piling requirement applies, were not common in the area. Success of the -5-foot standard does not imply equal success in higher dunes where the 16-foot embedment below grade may not penetrate to a sufficient depth. Storm-induced or long-term dune erosion is likely to leave insufficient piling penetration to support the buildings. Long-term erosion during the lifetime of a building may also threaten the buildings on even the -5-foot pilings that performed well during Hurricane Fran.

The most recent regulatory change began in 1993 when all CAMA oceanfront permits for buildings were conditioned to require them to be moved farther landward if threatened by erosion for more than two years. Threatened is defined as any building closer than 20 feet landward of the vegetation line along the beach. The condition has not been enforced to date, but will have a growing impact as long-term erosion encroaches on post-1993 houses.

Predicting Destruction and Damage in North Carolina's Coastal Buildings

North Carolina's history of coastal construction practice makes it possible to generalize future damage to buildings if the date of construction is known. For a specified storm-surge elevation and erosion profile, estimated building damage from flooding, waves and erosion can be significantly improved if additional building details and topography are known. Wave-sheltered buildings can expect typical flood damage to the interior and contents below the flood elevation, similar to riverine flood depth/damage curves. The NCSU research indicates it is reasonable to assume any building on a solid foundation will be destroyed where breaking waves of 1.5 feet or larger can occur. Piling-supported buildings, common since 1965, will lose underhouse living space or unfinished enclosures, but the elevated buildings have consistently remained in place in areas not subject to erosion. Flood damage to the elevated building is primarily caused when utilities such as wiring and plumbing extending into the lower enclosure walls are ripped from the elevated connections when the lower walls fail. Piling-supported buildings can be expected to be total losses when the estimated wave height reaches the floor elevation due to wave impact on lower elevation floor beams and joists. Typically, joist elevations are approximately one foot lower than the finished floor elevation. Any piling-supported building may experience limited damage but the elevated portion is unlikely to be destroyed as long as there is no erosion around the foundation and the waves remain below the floor beams.

In areas subject to storm-induced erosion, buildings on shallow foundations have been severely damaged, if not total losses. Unless a more detailed description of the foundation is available, it is reasonable to assume any small building experiencing erosion will be a total loss if constructed prior to 1965. Damage to piling-supported buildings can be expected to vary with date of construction. Piling-supported buildings constructed during the period of roughly 1965 through 1970 are the most difficult to generalize. During that period, a substantial number of the houses were constructed on small diameter, poorly preservative-treated pilings or discarded utility poles that have significantly deteriorated with time. Most remain standing outside the erosion area. With as little as one foot of erosion around the pilings, the small diameter and decayed pilings can be fractured by waves and floating debris. If pilings are lost in more than one row of pilings, severe damage or a total loss is likely. It appears reasonable to assume a percentage of total losses of buildings in the age group due to erosion. Addition research is needed to select an accurate percentage.

Most piling-supported buildings in erosion-prone areas constructed between 1965 and 1985 can be assumed to be constructed on pilings extending 8 feet below the original ground elevation. With increasing erosion, predicting the remaining piling embedment at failure can be estimated but cannot be precisely determined. Equations used to design piling foundation embedment include larger safety factors than used anywhere else in the building and are therefore of little value in predicting failure. Most of the small, piling-supported buildings in North Carolina have far less piling in the ground than design equations would suggest. Functional penetration depths have evolved from experience rather than design calculations.

Although successful outside erosion areas, the 8-foot-below-grade standard beginning in 1965 has been a common cause of failure where more than a couple feet of vertical erosion occurs. When a complete piling foundation failure occurs, the building can be expected to be a total loss. The trauma of foundation collapse and the likelihood of damaging waves dictate that destruction will be completed quickly. Building collapse is influenced by the loss of piling embedment and external forces such as waves on the foundation and wind on the elevated building. In buildings constructed on high ground elevations that are not overtopped by waves, it is common for one or two rows of piling to be completely undermined without collapse. Only the seaward section experiences erosion around the pilings. Similar effects are observed in both severe hurricanes and in smaller erosion-inducing storms where the wind loading is not a significant factor. If the elevated building survives the storm without significant damage other than the foundation, it usually can be repaired. Eroded pilings are replaced with longer pilings or short but deeper pilings are bolted or "sistered" to the original pilings. As more rows of piling are undermined in a single storm, the unsupported weight of the seaward end of the building will cause a rotation around the central rows of pilings, pulling upwards the most landward row of pilings. If more than two rows of pilings are eroded in any single storm event, collapse or significantly settling is likely in most buildings.

Buildings typically fall seaward into larger waves, leading to rapid disintegration of the walls once reaching the beach.

In buildings constructed on low ground elevations or where erosion occurs under the entire foundation, wind forces become a significant factor in the collapse of piling-supported buildings. Observations following Hurricane Fran offer the best guidance on shallow piling failure. Approximately 200 pre-1985, oceanfront houses, most on shallow pilings, were destroyed on Topsail Island and in Kure Beach. Precise measures of piling embedment remaining at the point of failure are not available, but failure appeared to occur when the average remaining penetration was approximately 3 to 4 feet, roughly half the original embedment. Frequently observed foundation remnants indicated that on typical post-storm beach slopes, little or no embedment remained in the seaward pilings. With the force of the wind the foundation rotated the central pilings, overloading and fracturing the landward third of the pilings. The seaward, two-thirds of the pilings were completely undermined or rotated in place without fracturing.

The post-1985 foundations — extending to -5 feet NGVD — were shown to have performed well in Hurricane Fran as described previously. The performance of the 16-foot below grade standard used in higher elevation lots was not significantly tested during Fran but the effectiveness likely will vary with elevation, depending on how close the tip penetration depth approaches -5 feet NGVD. Used on a ground elevation of +12 feet NGVD with a piling tip at -4 feet NGVD, most of the advantages of the -5-foot standard can be assumed. On a building site at +20 feet NGVD, the piling tip will extend to only +4 feet NGVD, making damage more likely when undermined.

The CAMA adoption of the oceanfront setbacks undoubtedly has prevented construction on some of the most erosion-prone properties and has moved some buildings farther landward. However, the long-range impact has been to delay, rather than avoid, future erosion damage. Where the state's historical erosion rates accurately predict the future, the setback can be expected to delay undermining by long-term erosion for the minimum 30-year multiplier following the construction, except where an exemption allows houses as close as 60 feet regardless of the rate on previously subdivided lots. A previous study of N.C. building location choices relative to the minimum setback found that most buildings were being constructed as far seaward as possible even if additional space was available to move farther landward on the lot (Stutts, Siderelis & Rogers, 1985). For long-range planning, the setback may delay the threat of long-term erosion but not avoid it. The setback is purposely based on the long-term average annual erosion rate, not the temporary erosion that will occur in a severe storm. The building code standards are expected to provide storm-induced erosion protection. The recent hurricanes have clearly shown that buildings constructed landward of the required setbacks can expect to be threatened by flooding, waves and erosion.

CAMA's 1993 relocation requirement for any later building threatened by erosion (closer than 20 feet landward of the oceanfront vegetation line) has no direct effect on damage from severe storms. It does affect the cost of long-term erosion since the owner must pay to move the building. The cost of relocation claims under the Upton/Jones provision of the National Flood Insurance Program between 1989 and 1995 averaged $32,000 (Rogers, 1995). Where there was insufficient room to relocate on the same lot, the claims did not cover the lost value of the original lot or the cost of purchasing a new lot for the relocated building. Relocating buildings has been a traditional and frequently used method of erosion management in North Carolina. The 1993 CAMA moving requirement has yet to be enforced on any building. However, as the modest beach houses prior to the 1980s have evolved to much larger, luxury houses, building floor areas have increased such that relocation to another lot may not be feasible due to transport barriers in some communities (Rogers, 1993). If a post-1993 building cannot be moved from the erosion threat, the regulations would require that the building must be demolished, a much greater loss in value for the property owner.

Construction Characteristics and Performance by Date of Construction

Construction Date	Construction Characteristics	Structure Performance
Pre-1965	Low elevation, shallow foundations	Flood, wave, erosion & wind sensitive
1965-1969	Small diameter, piling foundations	Improved flood resistance. Moderately wave, erosion & wind sensitive
1970-1984	16' pilings, 8' embedment	Effective for flood, waves and wind. Erosion sensitive
1985 to present	Deeper pilings on oceanfront	Flood, wave, erosion & wind tolerant. Good performance on low-elevation lots. Erosion-sensitive in high dunes
1993 to present	Relocation required for threatened structures	Relocation cost independent of damage
All dates	Location relative to shoreline position versus erosion rate	Collapse or uninhabitable due to long-term erosion

Discussion and Future Work

In North Carolina the unique history of construction regulations combined with a relatively high compliance rate where required and a far wider voluntary compliance, provides clear guidance to estimate the likelihood of flood, wave and erosion damage from severe hurricanes and long-term erosion. The date of construction is one of the most important factors in predicting damage from coastal storm events. Predictions can be significantly improved with additional data, including ground elevations, floor elevations, foundation type, underhouse enclosures and links to the local tax base. NFIP flood damage claims data is available through the National Flood Insurance Program. Efforts are under way to inventory the barrier island buildings affected by Hurricane Fran and the four other hurricanes impacting the area between 1996 and 1999. Conditions include storm surge return frequencies of approximately 120, 75, 37, 12 and 4 years. An additional inventory of oceanfront buildings statewide has been started. To date, partial funding has been obtained from a variety of sources and a pilot study for a detailed damage analysis of North Topsail Beach has been funded for 2001. Additional funding will be required for completion of the inventory and analysis of the data. Eventual analysis will link the inventory to NFIP claim payments from each storm and to local tax data. The study is expected to significantly improve our understanding of what was damaged and why. Results should also improve our ability to predict coastal flood, wave and erosion damage to buildings.

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