Lessons from Hurricane Hugo: The Need for Codes & Performance Criteria in Marinas & Coastal Structures

Formulating much-needed codes & standards for marina & coastal structure design requires the cooperative efforts of public agencies, engineers, building officials, legislators & insurers.

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Since Hurricane Hazel struck in 1954, South Carolina had been spared a direct hit by a major hurricane until September 22, 1989, when Hurricane Hugo slammed into the South Carolina coast. The eye of the storm advanced through Charleston Harbor, passing inland through the middle of the state (Sumter) towards Charlotte, North Carolina (see the map presented in Figure 1). Hugo was a one in 50-year event in Charleston, but was a one in 250-year event in Sumter and in Charlotte. Hurricane Hugo jumped from a Category II hurricane (winds of 96 to 110 mph) to a Category IV hurricane (winds of 131 to 155 mph) just prior to making landfall. The tidal surge accompanying the hurricane varied from 12 feet in Charleston Harbor at the center of the eye of the storm to approximately 20 feet on the north advancing edge of the eye of the storm (Awendaw, Cape Romain and McClellanville). From McClellanville, the tidal surge averaged about 12 feet to the Little River Inlet at the North Carolina / South Carolina boundary. South Carolina had less than 24 hours of lead time for hurricane preparation and the evacuation of barrier islands such as Isle of Palms, Sullivans Island, Kiawah and Folly Beach.

Marina facilities in South Carolina vary from small (from 30 to 50 slips) to medium (from 100 to 200 slips). Because of the normal tidal range (from eight feet in Hilton Head to five feet in Charleston), many marina facilities utilized floating docks constructed of timber, concrete or aluminum. Private and commercial marinas

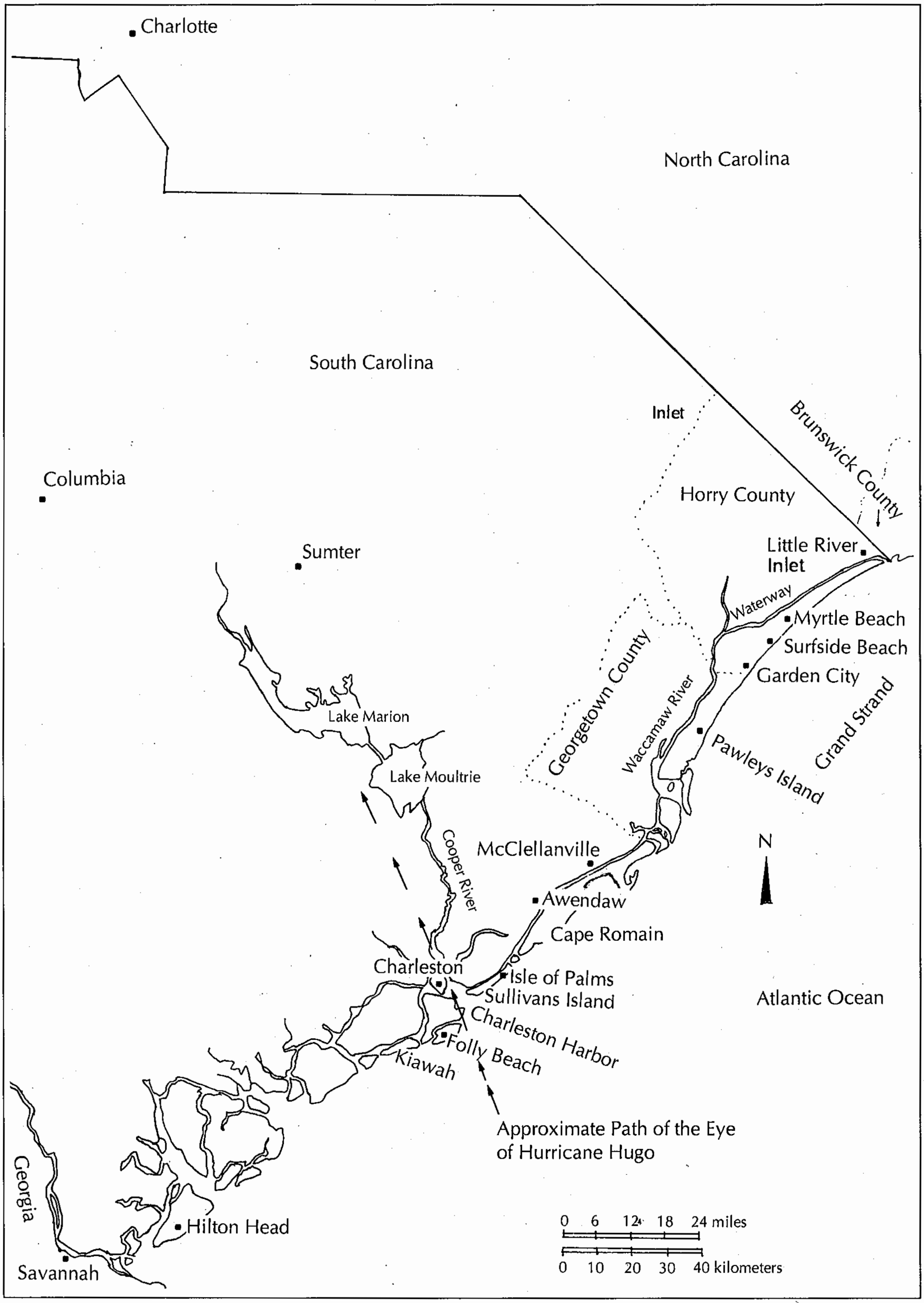

FIGURE 1. The approximate path of the eye of Hurricane Hugo through South Carolina.

were relatively new in South Carolina. Many of these marinas had been constructed in the past ten to fifteen years and were often operated by personnel with little or no experience with hurricanes. Public and private fishing piers were a long established usage in the Grand Strand area (Garden City, Surfside Beach, Myrtle Beach, *etc.*) where tourism is a major economic factor.

At that time South Carolina had no design standards for private residential piers, public or private fishing piers, or marinas. None of the coastal counties in the state had coastal structural or marina design standards or codes. However, the South Carolina Coastal Council had a written hurricane evacuation requirement in its *Operations and Maintenance Manual.*[1] Conformance to this document is a requirement for obtaining a marina permit in the South Carolina Coastal Critical Zone. However, no other public agency required plans for hurricane preparation, design, evacuation or recovery. None of these agencies required the participation of registered design professionals in the planning and design of marina facilities.

Immediately after Hurricane Hugo struck South Carolina, a comprehensive investigation and analysis of the performance of marina structures and operations during the hurricane was undertaken.[2] The hurricane / marina experience was further broadened by a visit to Puerto Rico in order to investigate other hurricane damaged marinas. In addition, other damaged structures and their reconstruction after the storm were monitored. These other structures included retaining walls, rip rap erosion control, fishing piers and residential floating dock and pier construction. Some of the more prominent design and construction failures are discussed here, with recommendations for minimum design considerations that could become the basis for the further development of minimum codes for marina structures in hurricane-prone areas.

Piles

The local practice in pile design in South Carolina favored the use of timber piles in marinas and coastal structures such as fishing piers, residential fixed piers and floating docks. Many of these piles were not designed by engineers since they were only one feature of contractor designed / installed structures. Soil conditions vary from sandy soils (Unified Soil Classification SM-SP) to organic clay (Unified Soil Classification OL, locally referred to as "pluff mud") over deeper marl (brownish green calcareous clay with slight sand content — Unified Soil Classification, MH). Residential pier structures — some as long as 800 feet — usually utilized jetted piles in lieu of driven piles. Lateral loads from wind and waves were often not even considered when determining pile sizes and pile penetration. The use of ten-inch and 12-inch square prestressed piles for horizontal loads had been growing in recent years. A locally accepted top of pile elevation was 12.0 feet above mean sea level (MSL).[3] This elevation would accommodate only a six- to eight-foot tidal surge (assuming the storm hits at high tide — adding a 1.5-foot freeboard for floating docks and a two-foot wave action during the storm).

By far, the most frequent failure in coastal and marine structures in South Carolina during Hurricane Hugo was pile failure. Both independent piles and piles within systems experienced a disproportionate number of failures. Many of the piles in fixed-pier systems failed from "pullout" due to uplift forces from wind and tidal surge. Others either broke at or near the mudline or leaned over from horizontal force. A final failure of piles in floating dock systems was found when piles did not have adequate height to restrain the floating docks during the tidal surge (see Figure 2).

Recommendations. A minimum timber pile size (tip) in coastal structures should be 25 inches in circumference for timber piles, and 12-inch square for prestressed concrete piles. Minimum pile penetration requirements based on local soil conditions should be developed. Pile penetrations of 20 feet for clay and 15 feet for sand should be the absolute minimum, regardless of local soil conditions. The minimum height of piles for floating dock structures should be set to withstand a designated hurricane's wind intensity and storm surge — *e.g.*, the minimum height for piles experiencing a 50-year storm occurring at high tide would be the mean high water elevation plus the height of the 50-year storm surge plus 1.5 feet for dock free board and two feet for wave action. Driven

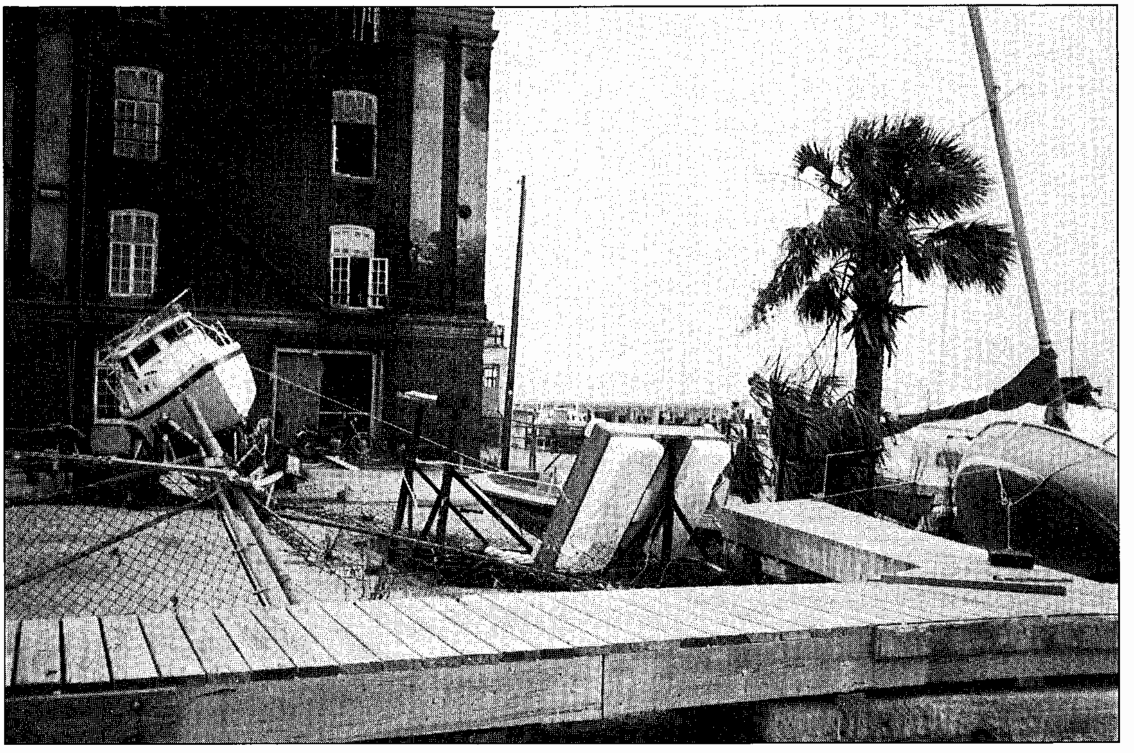

FIGURE 2. Hugo's storm surge took floating docks over the top of anchor piles and washed them ashore.

piles should be preferred over jetted piles and the jetting of piles in marinas and commercial pier construction should be permitted only under the supervision of a professional engineer. The use of old telephone poles for piles in salt and brackish waters should be prohibited. Piles for marina structures and commercial pier structures should be designed by a professional engineer.

Fixed Piers (Residential)

The coast of South Carolina includes large areas of tidal marsh that must be traversed with fixed piers before reaching deeper water suitable for navigation. Local dock builders and residential marine contractors utilized light structural components (nails, 0.375-inch galvanized bolts, butt splices on the nailers and side members, and toe nailed connections instead of straps). These structures served adequately while under vertical loads only. However, when confronted by the high winds, wave action and tidal surge caused by Hugo, they failed. Where pile penetration and pile size was adequate to withstand the uplift forces, the decking and handrails on the fixed piers were the first to go (see Figure 3). In some cases, if the pile cap connection was not adequate, the total deck structure (including stringers) with the handrail intact lifted off the pile or pile cap. Often, where pile penetration and size were not adequate to withstand the uplift forces, the entire structure, including piles, rolled over. This type of failure was especially prevalent in residential fixed piers that utilized small jetted piles in marsh areas (pluff mud soil condition).

Recommendations. There are many individual site conditions that have to be addressed on numerous residential installations. Because of their small scope, these projects usually do not have the involvement of a professional engineer. Often, a local building permit is not even required, so residential pier and dock projects escape local inspection by code enforcement officers. There should be some minimal standards for fixed-pier design. The only entities that are involved with all of these projects are the environmental permitting agencies (U.S. Army Corps of Engineers, Coastal Zone Management, *etc.)*. These agencies could promulgate suggested minimum guidelines of construction for these facilities.

Floating Docks

When anchored adequately, floating docks can move, deflect and relieve stresses. As previously mentioned, some floating docks floated over the tops of piles during Hugo's storm surge. Many floating docks failed from the loads transmitted by the boats that were tied to them. In addition, if the boats were not properly secured, they rubbed the docks, tore away from their moorings and caused impact damage throughout the marinas. Some floating docks failed as a result of impact from heavy floating debris (one floating tire breakwater broke away from its anchor and caused substantial damage in the marina it was supposed to protect). All floating docks suffered damage during Hurricane Hugo. However, the commercial "factory produced" docks fared better than locally produced docks and they were easier to repair or replace after the storm. Connections at the finger/main walkway junction exhibited weakness. Properly designed knee braces helped to sustain the lateral and twisting loads from boats anchored in the berths. Even concrete docks sustained damage through the wale system when they heaved against piles. Other dock systems tore apart at the connections between units (modules). From field observations, it appears that most floating docks failed after coming loose from their moorings (piles). Once they were taken out of their alignment, they were torn apart by twisting and bending. In many cases, the flotation billets were torn away from the structure (see Figure 4). Utilities in the dock systems were severed. Small cleats (eight inches and less) broke or were ripped from their moorings. Outside pile guides were torn from their moorings or were twisted when the docks broke loose.

Recommendations. The attention to adequate mooring (piles) and mooring devices (pile guides) will contribute substantially to the performance of the dock system. The piles must be high enough to restrain the floating docks during the storm surge. The mooring attachments to the docks (pile guides) must allow free movement while keeping the docks in alignment. This combination of design considerations will keep the system intact throughout the storm cycle. The stresses caused by boats beating against the floating docks during a storm are substantial, especially on the fingers and at the juncture of the fingers and the main walkway. It is essential that special attention be directed to the joints and connections within the dock system. Design and construction that assures that the flotation devices (floats) stay connected to the dock structure during rough weather is needed.

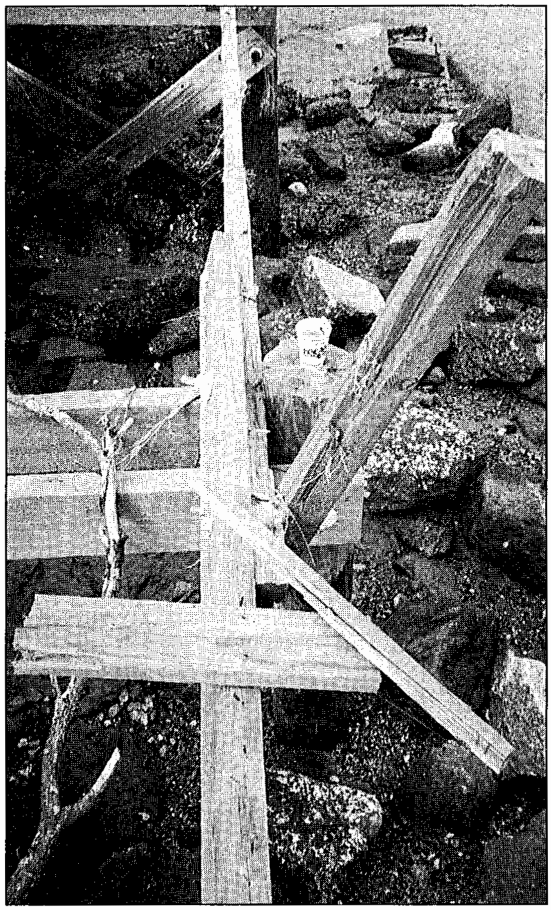

FIGURE 3. The decking and handrails fail first while the split pile cap and cross bracing have remained intact.

Retaining Walls, Stone Rip Rap & Other Beach Front Structures

Retaining walls on the beach front sustained severe damage from the storm surge and wave action. The Grand Strand area (Pawleys Island,

FIGURE 4. Floating docks were torn apart after tearing away from anchor piles.

Garden City, Surfside Beach, Myrtle Beach and North Myrtle Beach) is located between 75 to 110 miles northeast of Charleston along the coast (see Figure 1). Even these areas received a 12-foot tidal surge that caused substantial damage to ocean front hotels, businesses and residences. Structures that were protected by stone rip rap (one-man rip rap, with 30 to 150 pounds per stone) suffered less damage.

Similar structures near the storm's center (at Isle of Palms, Sullivans Island and Folly Beach) were destroyed by the combination of wind-driven waves and the storm surge. Even heavy stone rip rap structures such as groins on Folly Beach were damaged or destroyed. In all areas that had sand dunes, the damage was minimized because the dunes were sacrificial to the structures behind them. Once dunes were swept away, the structures behind the dunes (retaining walls, rip rap, swimming pools and building foundations) took the remaining force of waves, wind and rising waters, and failed (see Figure 5).

Timber sheet pile retaining walls on the beach sheared off at the ground line either from rising tides and surf, or outgoing tides that had washed the backfill and anchors from behind the retaining walls. Returns on the retaining walls helped, but in some cases the front retaining wall was torn away with the returns left intact. The coastal structures behind the beach, outside the Federal Emergency Management Agency (FEMA) velocity zone, exhibited little damage if they were designed and constructed with suitable, stronger materials, adequate tie backs and end returns.

Recommendations. The first line of defense for beach front structures is good planning. Locating habitable and commercial structures behind the high hazard zone is economical and effective. The next most effective method of protecting structures is to enhance and improve sand dune restoration and maintenance. In small storms and lunar high tides, this type of protection will be adequate. In larger storms, dune destruction will be sacrificial, but will help in protecting subsequent structures such as retaining walls and rip rap. Stone rip rap can be valuable for attenuating wave forces; however, if small size stones are used, they can

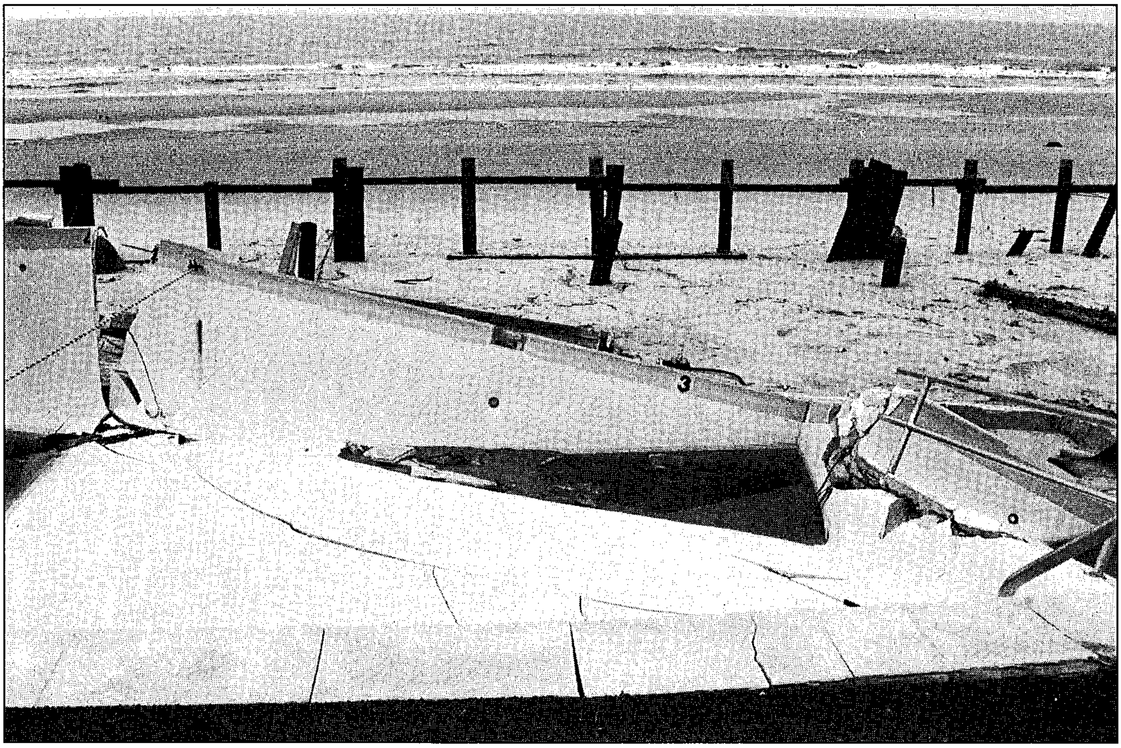

FIGURE 5. Sand dunes were washed away, exposing retaining walls and pools to the storm surge.

become missiles that can break glass, doors, *etc.*, during the storm. The rip rap should consist of minimum 200-pound each dense armor stone (granite) in conjunction with a geotextile membrane layer and gravel bedding between the heavy armor stone and the geotextile membrane. Where possible, retaining walls should not be utilized as the primary protection. However, if retaining walls are used, the toe should be protected with stone rip rap. If timber retaining walls are used on the beach front, the minimum thickness of sheets should be three inches. There should be returns on the ends of the structure when the retaining wall does not connect to the adjacent property. Special efforts should be made to design the structure in conjunction with the protection available on adjacent property, since the failure of an adjacent neighbor's structure may suddenly mean that the structure could be exposed from a different direction.

Fishing Piers

Pier fishing is very popular on the Grand Strand beach area (northern Georgetown County and all of Horry County) and in the southeastern beaches of Brunswick County, North Carolina. Although these areas were from 65 to 150 miles from Hugo's path (center), substantial damage to fishing piers occurred. The storm surge in Myrtle Beach (100 miles from Charleston) reached 12 feet. Most of the fishing piers were constructed of timber and all were over ten years old. Many had been repaired after past hurricanes, but still utilized older construction methods. The only fishing pier directly in the path of the eye of Hurricane Hugo was the Breach Inlet Bridge fishing pier located between Sullivans Island and Isle of Palms. This timber structure was mounted on the side of the bridge, but it was torn from its anchors in the bridge and was lifted by the tidal surge and damaged beyond repair. The remaining structure has been removed and may be replaced by a free standing structure soon. Many fishing piers were torn from their piling supports by the combination of uplift from submergence and horizontal forces from surf, drag

FIGURE 6. Sections of this fishing pier near shore sustained less damage. At the seaward end of the pier, pinned pile caps lifted off with the deck structure, thereby exposing piles and cross members to drag forces during the storm surge.

and wind. Sections near the shore (the first 300 to 400 feet) where pile length exposure (length from the ground line to the bottom of the pile cap) was less did not sustain as much damage as did sections in deeper water (see Figure 6).

The pile caps on many of these fishing piers were pinned through the top of the pile cap into the top of the pile with steel drift pins. The uplift forces lifted the pile cap and deck structure off, leaving piles with no top bracing. Once piles on the fishing piers lost their pile cap integrity, the cross bracing was not adequate to keep the piles intact. Scour at the base of piles exacerbated the problems by increasing the unsupported length of pile. Piles then came out intact, broke in the surf, leaned over or broke at the mud line. Once piles and deck structures were free in the surf, they continued inland to cause more damage to shore structures. From piles that washed ashore, it appears that some piles broke at midspan, probably from drag. The piles on fishing piers had cross bracing just below the deck structure. There were no cross braces below that point. The pile pairs were cross braced in the transverse direction and were not cross braced in the longitudinal direction. There was little evidence of the use of spiked grid connectors on the cross bracing to pile connection. Many of the galvanized bolts in the intertidal and splash zone had deteriorated (rusted).

Recommendations. There are no existing codes that are applicable to fishing piers. Only references to handrails and live loads are applicable from current building codes (Standard Building Code). Since these structures serve the public, their design should be dictated by professional engineers utilizing state or local agency mandated minimum design standards for materials and performance.

Fishing piers should be designed for a hierarchy of failure as follows:

1. Handrails and decking.
2. Stringers.
3. Pile caps.

FIGURE 7. A three-foot tidal surge and hurricane-force winds ripped out fixed-pier facilities in Fajardo, Puerto Rico.

4. Cross bracing.
5. Piles.

The handrail and decking failure still leaves a structure that can be made serviceable very quickly and economically. Once pile caps and cross bracing fail, it takes a major effort and outlay of funds to make the structure serviceable again. The minimum bolt size utilized in fishing piers should be 0.75 inches. Spiked grids should be used in the cross bracing and the split cap pile connections to the piles. Connector straps should be utilized if pinned pile cap connections are used. Metal connectors used in the intertidal and splash zones should be coated with coal tar epoxy after installation.

Puerto Rico & the Virgin Islands

Hurricane Hugo's path passed just west of St. Croix, Virgin Islands, then just east of Fajardo, Puerto Rico, on its northward advance toward the United States mainland. Hugo's sustained winds have been estimated at 125 miles per hour in St. Croix and 82 miles per hour at San Juan International Airport.[4] While there are no storm observations available from the Caribbean, the SLOSH Model (the National Weather Service storm surge computer program) predicted storm surge water levels of three to four feet above normal at St. Croix and the eastern end of Puerto Rico.[5]

Because of the small daily tidal fluctuation, marinas in Puerto Rico utilized fixed piers only. Many of the marina facilities are old and had been modified utilizing piles from existing structures. Hugo's wind and tidal surge ripped out many fixed piers that were located in exposed locations (see Figure 7). Structures — piles, abutments and fixed piers — that had been modified from the original construction often failed because the increased loads on the structures exceeded the original design. Many of the older concrete structures showed excessive deterioration (rust) in steel reinforcing and exposed metal. Recently constructed marinas that utilized professional design and modern materials survived Hugo with little damage.

Recommendations. Fixed-pier marina facilities should incorporate design considerations for the uplift that results from wind and storm surge. If the boats are to remain in the marina, fixed piers and piles should be designed for impact and anchoring live loads. Older marina structures should be reevaluated for their reliability in future similar hurricane events. Additions to older existing fixed-pier and pile structures should be constructed only when designed by professional engineers.

Reconstruction of Destroyed Coastal Marine Structures

In South Carolina, the docks, especially floating docks, have been upgraded. However, for the most part, the piles in floating dock systems are not being sufficiently upgraded to meet similar hurricanes in the future. Residential fixed piers and floating dock systems have not been upgraded. In the case of fixed piers and fishing piers, some have been upgraded, some have not been rebuilt, and on some the old mistakes are being repeated by the use of inadequate piles and pinned pile caps. Retaining walls and erosion control (rip rap), when permitted, have been reinstalled as before. The "beach retreat" policy of the South Carolina Coastal Council does not allow for the improvement of the structures that were destroyed. "One man" rip rap stone (135 to 150 pounds) has been used on many beach front projects. Contractor designs for replacement structures have also been used. Neither insurance companies, lending institutions nor permitting agencies have required professional involvement in many of these projects.

Conclusions

It is difficult to establish, on a case by case basis, the exact failure mode of structures during a hurricane. The combination of forces is varied and difficult to predict and does not necessarily approximate a set of formulas or a laboratory experiment. Only by looking at a number of installations with various types of construction can patterns of failures be developed that are conclusive and that should be translated into design standards and/or codes. Some design features should be obvious and historical in their application. However, with the advent of new materials, as well as the prevalence of design personnel with little experience, inexperienced marine contractors and developers that are trying to construct marina projects as economically as possible, the need for guidance in marina and coastal structure design has never been more apparent. ASCE Manual 50 *Report On Small Craft Harbors,* was published in 1969 and has not been updated since that time.[6] There is a committee that is active on a revision, but nothing is promised in the immediate future. A key design reference, "Small Craft Harbors: Design, Construction and Operations," by James W. Dunham and Arnold A. Finn, was published in 1974 and has not been revised since.[7] These factors — combined with a growing need to protect boaters, marina investors, marina insurers, financial institutions, adjacent property and the public at large — make the development of modern design standards a top priority.

Assuming that a very good set of design standards exists that could be used by competent marina designers, there are many marina projects that never have any involvement by registered design professionals. Many of these projects utilize designs developed by contractors or dock builders/manufacturers. Often, building permits and inspections by building officials are not even required on marina projects. If required, the inspectors often do not know what to look for; they have no code requirements to enforce. Insurance companies are insuring marinas without even knowing what standard of design was used in the facility. The marina insurers were hit hard by Hugo. Rates for insurance will likely be changing. Some insurance companies are beginning to give preferred rates to marinas that utilize design professionals. Lending institutions, likewise, have shown little concern for the design or the performance potential of marinas that are financed by them.

Environmental and resource agencies are reviewing marina permit applications with only a narrow view for their particular agency's consideration and little concern for navigation, boater safety, economic feasibility or public access to the water. The location, design, construction and operation of marina facilities is now being affected by these agencies that have little knowledge about the technical or operational aspects of marinas and coastal structures.

Engineers must recognize that structural adequacy and considerations for materials are no longer the only marina and coastal structure planning and design criteria. Because of increased public interest and environmental concerns, there are new considerations beyond the normal engineering purvey. It is time that total marina planning and design requirements be taken into account and a broad-based design standard that integrates most of these concerns should be developed. It is now obvious that this effort cannot come from only the professional design community or from government agencies. If engineers do not initiate positive leadership and action on marina standards and codes soon, the opportunity to control or affect the standards will be lost. In addition to the normal engineering design criteria, considerations for boater safety, marina operations, insurance, financing, international boating concerns and public safety should be addressed. The following factors are some that could be addressed in a new design standard:

1. Minimum hurricane or storm criteria for marinas should be developed. Adequate estimates of the winds and tides for different intensities of hurricanes can be obtained without much difficulty. The criteria should be developed around an expected return period for storms (*e.g.*, one in 50-year storm) occurring at the worst conditions (an astronomic high tide). If a marina is designed for this protection level, all parties — boaters, marina operators, *etc.* — will know how to react to an impending storm of a specified intensity.

2. Too much marina design is performed by contractors and dock builders who do not address all of the complex issues in the total marina design effort. In order to protect the public, government agencies need to set minimum marina planning and design criteria and need to require registered design professional involvement in marinas. (Maryland has currently instituted a program to develop a document that would satisfy this requirement for marina design and operation in areas that are subject to hurricanes.)

3. Marina design is not effective if the operation of the marina is not consistent with the design assumptions. If a marina designer assumes that boats will be evacuated from a marina in a hurricane and they are not (or they cannot be evacuated), then everything in the marina is at risk because of the erroneous design/operation assumption. If a marina owner cannot show a hurricane evacuation plan that demonstrates that the boats can be evacuated, the marina should be designed to hold the boats during the storm. Hurricane Hugo proved that complete evacuation of marinas is not possible.

4. Hurricane Hugo cost the insurers of marinas substantial money in claims. Indications are that the underwriters will be stricter on design or will withdraw from insuring marina facilities. Insurance companies and financing institutions have a responsibility to protect their investors and stockholders. The concerns for design life, design protection, and the amount of risk allocated to the boat in the marina and the marina facility should be made known to the design professional so marina designs that meet these requirements can be developed.

5. An internationally recognized standard for rating marinas is needed. International boaters need to know what level of service they can expect, what level of protection from the elements they can get, what additional services are available and what size craft can be accommodated. This rating system would encourage marina developers to address and assess the market better before committing to the project. Once a decision is made on the type of marina project they need to construct, the marina developer could then provide more realistic guidance about the project to marina planners and engineers.

6. State and local governments have a responsibility to provide leadership in setting minimum marina and coastal structures' codes. This goal may not be possible to accomplish on a nationwide basis because of the individual market and site-specific requirements for marina construction. Some elements that could be addressed in a marina design standards and construc-

tion code are as follows:

- Minimum hurricane/tornado design storm frequency (*e.g.*, one in 50-year storm).
- Design compliance certification by a registered professional engineer.
- Construction compliance certification by a registered professional engineer.
- Minimum piles sizes, and timber preservative treatment, if applicable.
- Minimum pile heights above mean sea level.
- Requirements for soils investigations and professionally engineered pile design to include pile penetration.
- Minimum loads for dock flotation, handrails and piers.
- Minimum floating dock freeboard under dead load and under combined dead and live load.
- Acceptable flotation materials for floating docks.
- Minimum gangway live loads, deflection criteria and angle at low tide.
- Minimum handicap design requirements.
- Minimum bolt and nail sizes.
- Minimum timber sizes and grades.
- Minimum corrosion treatment of construction materials.
- Minimum electrical requirements.
- Minimum water supply requirements.
- Minimum sanitary pump out requirements.
- Minimum parking requirements.

Summary

Hurricane Hugo probably caused more property damage than any storm in history (the estimate of damage is at 9 billion dollars). However, it is also the best documented storm in history. The lessons from Hurricane Hugo should not be forgotten. South Carolina residents were lucky — the state leadership evacuated areas in a timely manner. A more densely populated area may not be able to act so effectively. Engineers now have the knowledge and the ability to design for the next hurricane disaster. However, in the interest of their profession and the public, they need to secure the aid of building officials, government agencies, insurers and legislators in developing and implementing new codes and standards for marina and coastal structure design.

NOTE — *The author visited Puerto Rico in conjunction with a joint post-disaster evaluation by the International Marina Institute and the Puerto Rico Sea Grant College Program at the University of Puerto Rico.*

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