SECTION II

Marina Hurricane Design Considerations

A. Relevant Terminology

Bulkhead: A wall subjected to varying hydrostatic water pressure plus waves on one side and hydrostatic and soil pressure on the other. Bulkheads can have several failure modes and should be designed by a licensed structural engineer.

Design Loads: Forces that must be carried by the structure being designed. Vertical loads include the Dead Load (the weight of the structure) and the Live Load (the "extra" load imposed on the structure by people, baggage, etc.). The live load may move about. On floating structures, freeboard is specified under both dead load and live load conditions. The buoyancy of walkways and wooden support beams will apply an upward vertical loading to fixed, pile supported structures when they are submerged. These forces must be addressed for severe storm conditions. Horizontal loadings caused by wind, current and boat or debris impact must be included, and the forces must be applied at the correct location. Under maximum design conditions, such as imposed by a hurricane, the forces would be applied near the top of the pile. The vibratory nature of these forces can have a more detrimental effect than a load applied smoothly in one direction.

Design Period: The projected recurrence period for a storm of a given strength. The design period indicates the probability that a storm of that magnitude may occur in any given year.

Recurrence Period (Yr.)	5	10	25	50	100
% Chance in Any Given Year	20%	10%	4%	2%	1%

Fairway: The clear distance between two rows of docked boats that is traversed when leaving or entering a slip. When no strong currents or wind forces exist, the fairway should be 1.5 to 1.75 times the length of the longest docked vessel.

Fetch: The length of water over which wind waves are generated. Longer fetches allow higher waves.

Freeboard: The height of the structure above design water level.

Pile Cap: The device that provides a connection between the pile and the structure being supported by the pile. This is a critical link in the design of pile supported structures because it must transmit all the horizontal and vertical forces to the pile without becoming detached.

Riprap: A protective layer of quarry stone, usually well graded, with a wide size limit and randomly placed to prevent erosion and scour. The size of the stone is dictated by the expected

wave energy. In severe wave climates, a larger, more uniform layer of stone called the armor layer may be placed on top of the riprap.

Scour: The removal of underwater material by waves and currents, especially at the base or toe of a shore based structure such as a bulkhead. Scour is increased during severe storm events because the storm surge provides deeper water thus allowing larger waves to reach the bulkhead.
Significant Wave Height: The average height of the highest 1/3 of the waves of a given wave group.

Storm Surge: A rise in water level above normal levels due to wind stress or, in the case of a hurricane, wind stress plus very low atmospheric pressure. Storm surge can raise water levels 17 to 20 feet causing extreme flooding. The impact worsens because the deeper water levels caused by storm surge allow larger waves to approach and break on otherwise protected structures.

Tidal Range: The difference in height between consecutive high and low waters. The tidal range for Spring Tides (which occur at or near the time of the new or full moon) is larger than the tidal range for Neap Tides (which occur near the time of quadrature of the moon, i.e. half moon points).

Tide: The rise and fall of the water level caused by the gravitational attraction of the sun and moon. Astronomical tides do not take into account the potentially large changes caused by weather. There are several tide water levels that are used as references in marine design and they include:

- **MHW** - Mean High Water is the average high water elevation over a 19-year astronomical cycle.

- **MHHW** - Mean Higher High Water is the 19 year average height of the higher high waters of a semi-diurnal tide which exists when an area has two high tides each day rather than a diurnal cycle with only one high water per day.

- **MLW** - Mean Low Water is the average low water elevation over 19 year astronomical cycle.

- **MLLW** - Mean Lower Low Water is the average height of the lower of the two low waters of a semi-diurnal tide cycle.

Waves: Periodic undulation of the water surface normally generated by wind or boat wakes. The three important parameters of waves are wave height, wave period (the time between 2 subsequent wave crests), and direction. Although it seems obvious that higher waves have more energy, it may not be as apparent that long period waves (10 to 15 seconds) have more energy than short period (2 to 4 second;) waves. Wave data is most often hindcast; that is, computed using known wind velocities over measured fetches to predict wave heights and period. If available, data taken from wave gages that measure actual wave height, period, and direction is much preferred over hindcast techniques. In shallow water, under most conditions, the wave can be no higher than 80% of the water depth.

B. Issues of Concern

In marina design, perhaps the greatest concern lies in the almost total lack of established design standards and building codes nationwide. Design and construction of even the smallest marina is complex, multi-disciplinary and requires a number of considerations combined with a vast array of data requirements. Each facility is site specific, market specific, environment specific, and use specific. Proper engineering and design of a marina requires the involvement of licensed design professionals who are experienced in marina planning, design, and construction. The lack of established design standards and building codes increases the need for professional involvement.

It is difficult to establish the exact failure mode of structures during a hurricane. The combination of forces is varied and difficult to predict and does not necessarily follow a set of formulas or a laboratory experiment. Only by looking at a number of installations with various types of construction can we begin to identify patterns of failures that are conclusive and translatable into design standards and/or codes. Some design solutions should be obvious and historical in their application, but with new materials, new inexperienced marine design personnel, outdated design guidelines, inexperienced marine contractors, and developers that are attempting to construct marina projects as economically as possible, the need for guidance in marina design has never been greater. The above factors combined with a growing interest in boating and the need to protect boaters, marina investors, marina insurers, adjacent property, and the public at large, make the development of modern marina design standards a top priority.

Assuming that very good design standards and criteria are available and usable by competent marina designers, there are many marina projects that still never have any involvement by registered design professionals. Many of these projects utilize designs developed by contractors or dock builder/manufacturers. Often, building permits and inspections by building officials are not required on marina projects. If inspection is required, the inspectors often do not know what to inspect. They have no code requirements to enforce. Insurance companies are insuring marinas without knowing the standards of the design used. Lending institutions, likewise, know little of the design or the performance potential of marinas.

Environmental and resource agencies have, in the past, reviewed marina permit applications with 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 determined by agencies that have greater knowledge about, and positive concern for, marinas.

The remainder of this Chapter is intended as a preliminary introduction to marina planning and design concepts related to significant storm events. This information shall be useful for inexperienced design professionals, marine product manufactures, new or prospective marina owners and others who wish to become familiar with marina planning and design concepts. It is not a definitive design document, and the writers assume no responsibility for its use.

C. Basic Planning Considerations

First: Hire a licensed design professional and require her /him to at least review and seal all drawings and specifications provided to you. If possible, let design professionals be involved in the permitting process.

Second: Develop and commit in writing to a specific severe weather operation policy. The design professional should be requested to provide cost/benefit trade-offs during the decision process.

Third: After receiving a written severe weather operations plan the marina design professional should use the best reasonably available technology and judgment to predict design loads that will actually be applied throughout the marina. The design return period on hurricanes should be balanced against the expected life of the marina, and compliance with local codes and ordinances. Keep in mind that codes are minimum design criteria and increased strength and reliability may be more economical in the long run.

The recommended design period for hurricanes (wind and tidal surge) is normally 50 years (2% probability, in any given year) and 25 years (4% probability in any given year) should be considered the absolute minimum design period. This is true even if the expected life of the offshore facilities is less than 25 years. Operation plans that assume boats will leave the marina are detrimental and unrealistic. Even if boat owners were willing to remove their boats, they may be unable to get to their boats or they may be prevented from moving their boats due to severe weather or channel obstructions. If they do move their boats, passing transients may dock in the empty slips.

Fourth: In order to protect the public, government agencies have a responsibility to set minimum hurricane planning and design criteria and to require the involvement of licensed professionals in marina design. The marina design professional should exhaust this source in his quest for applicable design data.

Fifth: Dock manufacturers' literature is developed to assist in marketing docks. Claims about performance during past hurricanes can be misleading. Marinas are extremely site specific. Do not rely completely on dock manufacturers' literature, especially those that promote standard designs for specific wave heights, wind loads, etc. Dock manufacturers and suppliers should be required to submit design calculations and documents showing that they comply with site-specific marina design requirements. The number of years in the dock manufacturing business, a history of performances in hurricanes and the service provided after the storm are important criteria to consider when selecting and specifying dock manufacturers.

D. Factors to be Addressed

Marina Siting: Select sites that offer protection from hurricanes.

Wind: Velocity, direction and duration are critically important in the design of dry stack facilities, and winds also apply forces to docked boats which translates into forces on docks and pilings and other anchor systems. Potential wind blown missiles include dock boxes, signs, dinghies, sheet metal panels from buildings, and all other unsecured loose objects. Navigation of vessels into or out of the marina or the use of marina equipment such as fork lifts may be severely restricted.

Waves: Height and period are important because they determine the force on the dock system as well as on the land/water interface (either bulkheaded or ripraped shoreline). Waves affect not only boats moving into, out of or within the marina but may restrict movement of personnel on docked vessels and prevent access to or from vessels on either fixed or floating docks or swing moorings.

Tides and Storm Surge: The combination of these provides the base elevation to which waves and required freeboard must be added. Begin with the level of high water (Mean Higher High Water, MHHW, is a good choice), and add the increased water level due to storm surge to get the basic starting water level. For example, a mean spring tide at Ocean City is +4.2 ft above Mean Low Water plus a 17-ft storm surge similar to that seen in Charleston during Hugo (1989) equates to +21.2 ft. For this extreme example a fixed, pile supported walkway or dock at an elevation of 21.2 ft would be level with the still water level and even 3.0 ft waves would create serious problems for individuals using the facility. In the case of a floating dock, the freeboard of the dock must be added to pile lengths just to keep the dock from floating away! The implications of the combined effects of tide and storm surge on landside facilities at the marina are obvious.

Currents: Currents have the same effect on boats and docks as the wind except that the force is applied to the portion of the boat below the waterline. Currents may vary in both velocity and magnitude due to changing tides. During severe storm events, currents may carry a significant amount of large debris, which adds additional impact forces to boats and docks when they are struck.

Soils: Soils must be tested by a licensed soils engineer to determine horizontal bearing capacity relative to the forces applied by wind forces on the boats and through the docks. One boring per 10,000 square feet of area may be sufficient but these must be taken in the vicinity of the piles offshore, not at an on-shore location chosen simply for convenience. For fixed pile supported walkways and docks, vertical bearing capacity is required along with the ability of the pile to withstand the buoyant forces of a totally submerged dock system. Soil borings must be deep enough to define the total strata that the piles penetrate, plus an additional 5 feet.

Access: Access is of concern during storms for those desiring to leave the marina or seeking shelter within it. Access will be hindered by high, gusty winds, large irregular waves, and possibly strong currents carrying much debris. Harbor entrance channel widths should be at least 100 ft and even using these criteria movement into or out of the marina may be prevented by other boats sinking in the channel. Bridges may remain closed and may be inoperable after the storm.

E. Basin Planning

Geometry: Because much of the wave energy striking a vertical bulkhead will be reflected, long parallel opposing bulkheads should be avoided. Round corners should be included along bulkheads and sloping banks protected with riprap or paving blocks should be used where possible to dissipate the wave energy.

Dredging Depth: Dredged depths should not be excessive. The excess dredged depth is expensive to dredge, disposal of the material is costly and the increased depth will raise the cost of anchoring the docks because piles will need to be longer (to support the docks) and larger in diameter (to withstand the additional bending moments).

F. Land Planning

Parking: Anticipate that all boat owners will be spending two or three hours on their boat 24 to 48 hours prior to the storm. One parking spot for each two wet slips for recreational boaters plus two parking spots for each commercial fishing vessel should be adequate unless local building codes dictate otherwise.

Pedestrian Access: Sidewalks, walkways, and gangways should be lit, above water and well marked should they become submerged due to storm surges. Walkways that are expected to become submerged should be well maintained and designed without steps or other obstacles that could pose a tripping hazard when hidden under water. Provide sturdy post on railings to mark the edge of the walkway and to provide handholds.

Ancillary Buildings: An ancillary building should comply with local building codes but should also be protected from impact damage due to flying and floating debris. "Floating debris" could include a 50-ft boat that has broken away from its moorings, a broken pile, or a piece of floating dock. Documents, equipment, and supplies needed immediately after the storm to provide security, minimize additional damage, and begin recovery should be secured in a safe, dry location. A well designed storm drain system, especially behind bulkheads and seawalls will minimize erosion or possible collapse when the storm withdraws. Buildings should be designed without canopies or wings, and tall trees should be located away from structures. Miscellaneous equipment such as ice machines, drink machines, etc. should be located in structures or in areas that will minimize their potential for wind and water damage. Facilities should be located at elevations higher than the expected tidal surge. Trailers should be secured with hurricane anchors.

Emergency Access: Emergency access lanes should be addressed when laying out the facility. These should be marked in accordance with local fire code requirements.

G. Channel Entrance & Wave Attenuation

Jetties and Breakwaters: These aids to navigation may provide sheltered water while entering or leaving the area of the marina but the level of protection they afford and even the survivability of the structure itself may be in question, depending on the severity of the storm. To be of value during a severe hurricane the riprap or armor stone must be of sufficient size to protect the structure from the increased design wave height incurred during the storm and the height of the structure must be sufficient to provide the desired wave attenuation. Consider possible overtopping during the storm surge in defining the height of the structure.

Wave Attenuation: Additional wave attenuation may be required within the marina to maintain an acceptable climate for boaters to move about on their boats in preparation for the storm, especially if long period waves can approach the marina from the open sea by passing straight through the entrance channel.

H. Inner Harbor Structures

Basin Perimeter: All basin perimeters must be designed for the selected storm recurrence interval. Bulkheads designed by a licensed structural engineer should withstand the oncoming storm as well as remain intact during the receding tide without excessive scour of the backfill behind the bulkhead, which could cause failure of tiebacks and subsequent failure of the entire structure. The inclusion of bulkhead returns and good drainage through filter cloth and weepholes will reduce scour. As previously mentioned, a sloping armored perimeter has several advantages, including reduced reflection of wave energy, but it also requires additional space within the marina and rough surfaces may pose a hazard to boats.

Fixed Docks: The fixed docks must be designed for vertical and horizontal forces. All fixed structures must be designed to withstand upward vertical forces caused by total submersion of the structure and any connected appurtenances. Fixed docks and pile-supported walkways should use split pile caps bolted with double dip galvanized hardware. Pile caps spiked onto piles will disconnect from the piles when submerged due to uplift forces caused by the buoyancy of the decking, stringers, etc. Dock boxes shaped like polystyrene tubs and securely attached to the fixed walkways will provide additional buoyancy and apply an upward force to either separate the walkway from the pile or pull the pile out of the ground. On fixed, pile supported structures, either a metal connector or adequate lap must be provided in butt and lap joints to prevent the joists from becoming dislodged from the joints. The beam joints should be staggered rather than locating all the joints in a line over the pile cap, which would then act like a hinge rather than a continuous beam. Connection hardware, such as cleats, must be adequately sized for the moored vessel and must be bolted through the dock using appropriately sized galvanized or stainless steel hardware.

Floating Docks: When floating docks are in the plans, they should be designed for full slip loading unless there are absolute assurances that the boats will be removed. The design must account for hurricane wind load and storm surge simultaneously with a Spring high tide. If the marina is adjacent to critical shipping lanes or vital installations that might be affected if

the floating docks are damaged or dislodged and boats sunk, serious consideration should be given to increasing the design storm recurrence interval. Commercial dock systems may perform better than locally built, contractor constructed docks. In addition, the owner should be aware that the manufactured systems may also lend themselves to easier repair and reinstallation. Ancillary equipment (utilities, dock boxes, etc.) should be integrated into dock systems that will make hurricane preparation and recovery easier (e.g. removable power pedestals, dock boxes, gangways, etc.). Since most failures occur due to pile failures, a licensed professional should assure that the piles are of adequate diameter, have adequate penetration and are of adequate height to account for the high tide, storm surge, wave heights, and adequate freeboard for the dock. Connection hardware sized adequately for the moored vessel and bolted completely through the dock with galvanized or stainless steel hardware is essential.

Moorings: If open moorings are used, both bow and stern moorings should be installed to keep boats properly oriented, reduce swing and provide an additional factor of safety. Proper inspection and preventive maintenance of swing moorings may be more difficult than for fixed or floating docks, but is absolutely essential.

Gangways: High wind loads can make gangways fly horizontally and flap in the wind. The hinge connection on the gangway undergoes torsion and the gangway is subjected to racking forces. Unless gangways are disconnected, the waterside end may be forced above the floating docks and utilities trapped between the dock and the gangway. Utilities should be nested securely under the gangway with a loose loop connection at the bottom to allow movement where the gangway meets the floating dock. The floating dock may be crushed as well but increasing the dock offset may alleviate dock damage.
The gangway hinge should allow for torque from twisting and racking by the gangway during the storm. A better solution might be to put quick disconnect couplings on the utilities and the gangway and remove the gangways just before the storm arrives.

Dry Stack Facilities: The dry stack facilities must withstand the extreme wind forces exerted on the large but lightweight structure. Tremendous uplift forces are applied to the foundation. Failures begin as the metal skin on the sides and roof peel away leaving the remainder of the structure and the racks to independently withstand the wind loads. Special attention should be paid to uplift forces on the roof structure. Rack supported roof structures may require additional design analysis.

Launch Facilities: Launch facilities may become overburdened with boaters attempting to remove their boats during the inclement weather preceding the hurricane. The inclement weather may require extra time for tie downs and boaters may be shorthanded due to limited time available to get help before the impending storm. Therefore, extra staging areas may be required due to additional loading time. Marine travel lifts may also keep the launch ramp busy, and the inclement weather will hinder travel lift and forklift operations. Assume that all operations will be at about one-half normal speed during the period of inclement weather before the storm.

I. Marina Systems

Fueling: Fuel pumps should be installed above the high tide plus storm surge elevation for the selected design storm and fuel tanks must be counter weighted sufficiently so that they will not rise if they become both empty and completely submerged in saturated soil.

Sanitary System: Landside sanitary holding tanks must be designed and counter weighted so they will not float when empty and completely submerged. The cover should be bolted down during the storm to prevent escape of the sewage.

Electric and Communications: Transformers and utilities on floating docks will be destroyed when the docks are lost and associated items such as power pedestals, gas pumps, lights, pump-outs, dock boxes, etc. will also be damaged and lost. Transformers should be located on land whenever possible and the other items should be removed and stowed. Radio antennas should be designed to withstand the maximum wind velocities expected.

Hazardous Waste: Waste oil, antifreeze, and other hazardous waste should be designed to meet the local, state, and federal requirements. Storage areas should be designed to be above the floodplain.

Other Systems: Trash and Debris containers such as dumpsters should be well anchored and secured to prevent them from floating away and becoming hazards. They will be needed immediately after the storm.

J. Useful Tips

The following comments come from a variety of sources over several years. They are but some of the numerous factors that are considered in marina design.

- Dock assemblies are usually connected with halted semi-rigid joints to act as a continuous beam or are hinged to allow flexibility. Hinges between docks experience damage because motions or forces are applied for which they were not designed.

- Be alert for new materials that offer improved resistance to hurricanes or can be easily repaired.

- All hardware in the marina environment should be hot dip galvanized or stainless steel.

- All piles must be chemically treated or be naturally resistant to decay and marine borers, such as the tree Greenheart (*Nectandra rodioei*). Piles should be inspected at six-month intervals for decay or rot, cracking or splitting, or wasting away by infestation by marine borers.

- Docking systems should be designed with a balanced approach. This does not preclude designing selected parts to a lower level of strength, allowing certain portions to be sacrificed to prevent total loss of the system.

- When designing fixed, pile supported walkways, the decking should be designed to fail before the handrail fails. The deck structure and piles should be designed to fully withstand the wind, external impact, and uplift forces of the storm.

- A failed pile can cause an entire system to collapse. Design piles for the most extreme event.

- When rebuilding after a hurricane, do not merely replace failed parts and pieces but upgrade piles and other selected structures so that similar failures are prevented or minimized in the next storm.

- If the entire marina cannot be designed to hold the boats during a hurricane, design a portion of the marina to withstand the storm.

- Hurricane protection is a combination of design and operation. What is not covered by design should be covered by the marina operation, evacuation, and recovery plans.

- Whatever is not covered by design must be covered by insurance or it is at risk.

- Keep copies of marina permits, design drawings, and shop drawings in a secure, watertight location.

- Floating breakwaters and wave attenuators are ineffective for wave periods longer than approximately 4.0 seconds.

- Repairability of docks should be a design consideration.

- Small cracks in bulkheads that allow backfill material to escape when overwashed should be repaired using engineering fabric or other techniques, and kept in good condition.

Summary

Some marina failures are inevitable due to the exposure and the dynamic nature of the marina environment. Most observed failures, however, result from inattention to design details, poor layout or marina planning, lack of maintenance, shoddy product manufacture, lack of understanding of what a marina is and who it serves or underestimation of storm effects. A true cost-benefit analysis should be made of all marina components and attractive, low, first cost products scrutinized as to their suitability for the intended use and environment. When considering marina survivability during a hurricane or similar severe storm events, the aforementioned effects are magnified considerably.

Recognition

This chapter was developed in conjunction with information published by Jeff Bliemel, Coastal Engineer, in the *Maryland Guidebook for Marina Owners and Operators on Hurricane and Severe Weather Preparedness.*