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TWO TEMPESTS: A CASE STUDY ON CAPTURING NEARSHORE HURRICANE WAVE CONDITIONS

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ABSTRACT

Measurements of the shallow water hydrodynamic characteristics of major hurricanes are required to develop appropriate design and policy responses and to minimize impacts from future storms. Several agencies manage measurement programs that had operational systems within the nearshore zone of influence of major hurricanes in recent years. These gages represent widely different approaches to the challenge of capturing extreme event data and each exhibited both successes and shortcomings. In general, the closer the instrument site was to the storm path and the shallower the water, the more likely the system was to experience problems with the sensor, the platform, and/or data recovery.

The various systems and their results are described. All methods were partially successful in that some of the systems operated during the hurricanes and useful data were eventually recovered, yet in each of the cases examined the gages either failed or exhibited data quality issues during the peak conditions. Nevertheless, they are the only available measured time series of wave conditions in shallow water close to a major, landfalling hurricane. Lessons learned for making these types of data less rare in the future are discussed. Options for improving utility of extreme measurements to the practicing engineer are presented.

INTRODUCTION

In addition to their tragic social and economic impacts, Hurricanes Ivan and Katrina marked a sea change in many arenas, from coastal geomorphology and climatic statistics to public perception on coastal land use and disaster management. Details of their hydrodynamic characteristics, particularly in shallow water, are extremely valuable in developing appropriate coastal engineering design and policy responses to minimize future impacts to coastal infrastructure from such massive storms. However, obtaining any ocean wave data is a difficult and expensive undertaking; not surprisingly capturing extreme conditions is even more challenging. Actual in-situ hydrodynamic observations within close proximity to a hurricane have proven particularly elusive due to their limited temporal and spatial footprint.

Perhaps counter intuitively, shallow water hurricane measurements are even rarer than deepwater observations. For purposes of this paper, a site in "close proximity" will be defined as within 100 nautical miles (185 km) of the center of a major hurricane as it came ashore, and shallow water will be defined as less than 20 m water depth. Forristall [1] summarizes 18 data sets from deepwater (60 m plus) observation stations during four recent hurricanes. Only 9 examples of shallow water stations were identified that met the criteria for this case study.

There were several US federal agencies which manage measurement programs that had operational systems within this zone during the active 2004 and 2005 hurricane seasons. They include: the US Army Corps of Engineers (COE), the National Oceanic and Atmospheric Administration (NOAA), and the Office of Naval Research (ONR). Gage types in this case study include bottom mounted pressure sensors, large oceanographic buoys, and small, event-deployed buoys. Distance from the instrument site to the hurricane's path range from ~ 100 nm to essentially zero. Some were there by design with the specific goal of measuring large waves, while others had more general operational or process missions and just happened to be in the right place at the right time. These gages represent widely different approaches to the challenge of capturing extreme event data and each exhibited both successes and shortcomings. What success has been achieved has been as much the result of luck as a focused project.

TRIALS (AND TRIBULATIONS)

Programs with a Hurricane Mission

A program dedicated to capturing hurricane conditions has historically required a significant and open-ended funding commitment. Typical costs for installing and operating a single in-situ wave gage for even a few years run several hundred thousand dollars [2]. The major factor is the recursive nature of the design and logistics constraints. Gages at multiple sites must be deployed and operated for multiple years so they will be in place and operating when and if a hurricane strayed near. Large, robust gages are required to have sufficient electrical power (grid connected, batteries, and/or solar panels) for long deployments. Large instrument systems require large vessels, crews, and equipment, and relatively calm conditions to safely deploy, so instruments must be deployed far in advance of the conditions of most interest for engineering applications. With a target zone stretching from Mexico to Canada and finite resources, it was the epitome of a "hit or miss" effort.

More recently, advances in electronic miniaturization have produced wave instrumentation with impressive memory and telemetry capabilities that are very small and inexpensive [3]. Of course, small instruments with small battery packs are constrained to short-term deployments. However, low acquisition and deployment cost permit rapid, event-triggered deployment. The utility of this approach was proven during Hurricane Katrina.

Lake Pontchartrain Hurricane Wave Monitoring Program: The US Army Corps of Engineers (COE) District New Orleans managed the Lake Pontchartrain Hurricane Wave Monitoring Program (LPHWMP) under the Lake Pontchartrain and Vicinity Hurricane Protection Project (LPVHPP). The LPVHPP provides hurricane protection for the metropolitan New Orleans area. Wave run-up is an important parameter in the design of hurricane protection levees. The intent of the Wave Monitoring program was to obtain wave data to use to calibrate, test, and verify numerical wave models that generate the input waves for the wave run-up calculations under design wind and surge conditions.

The gages used for the project were miniature hand-deployable buoys made by Neptune Sciences, Inc (NSI) that are less than 60 cm (2 ft) long and weigh less than 4 kg (8 lb). In addition to its wave sensor each buoy has a GPS receiver. Both wave and position data are stored in internal memory in the buoy but are also broadcast on the UHF radio band. Details of the system design, including the Mini Wave Sentry buoy and the strategic approach of the episodic gage deployment program, can be found in [4].

Two test deployments in small storms proved the viability of the event-deployed method. When Katrina threatened New Orleans on Saturday, September 27th, 2005, three buoys – Gage # 22, 23, and 24 - were deployed about 1 km (0.5 nm).north of the south shore of Lake Pontchartrain in 7 m of water. This site is directly offshore of the entrance to the 17th Street Canal, which would become one of the major failure points of the city's flood protection system. Hurricane Katrina made landfall early on the 29th, passing just east of New Orleans. Winds were from the northern quadrant near 1430 UTC as the storm made its closest approach of 25 nm from the gages placing the gages at the maximum available fetch during the highest wind speeds. Figure 1 shows the relative position of Gages 22 and 23 with the HRD hindcast Katrina wind field contours at 1500 UTC.

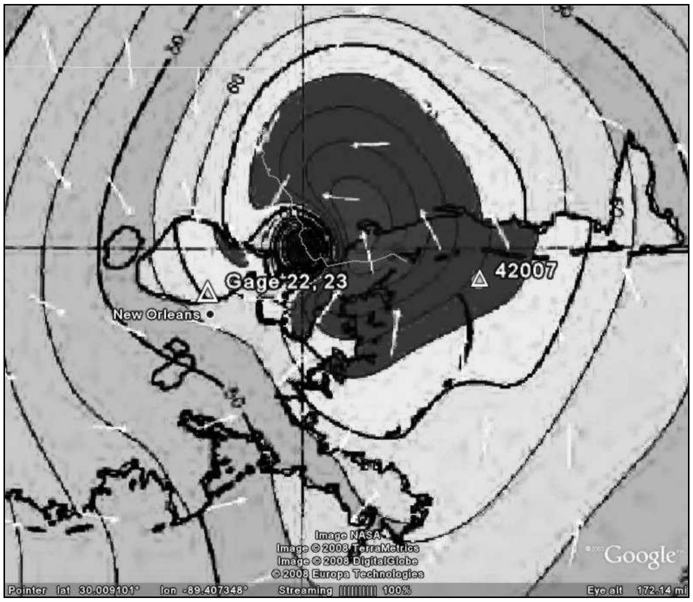

Figure 1 - COE gages 22 & 23 and NDBC station 42007 with Hurricane Katrina modeled wind field at 1500 UTC, 29/08/2005

The receiver for the data telemetry option was not installed so recovering the data required recovering the gages. Time was a critical factor since the small buoys could be easily swept up in the massive cleanup operation that would soon commence. One of the buoys (Gage 23) was recovered at its deployed location on September 7th; a second (Gage 22) was found washed up on the south lakeshore the following day. Gage 24 was found onshore by emergency personnel and eventually returned. All three buoys functioned electronically. Of the buoys found ashore, Gage 22 maintained its station until after the storms passage but # 23 drifted off station on the 28th and collected no storm data. [5]

SAX04 Project: The Office of Naval Research (ONR), Coastal Geoscience Program sponsored the SAX04 project to better understand the role of seafloor morphology in the generation and dissipation of hurricane waves across the continental shelf [6]. Nine sites offshore of northwest Florida were instrumented bottom-mounted pressure sensors (Figure 2). The instrument tripods were equipped with acoustic releases to send a recovery line with a float to the surface. Sites 1, 9, and 2 met the criteria of interest for Hurricane Ivan. Figure 3 shows the location of Sites 1, 2, and 9 with the radar image Hurricane Ivan as it makes landfall at 0702 UTC on September 16, 2004.

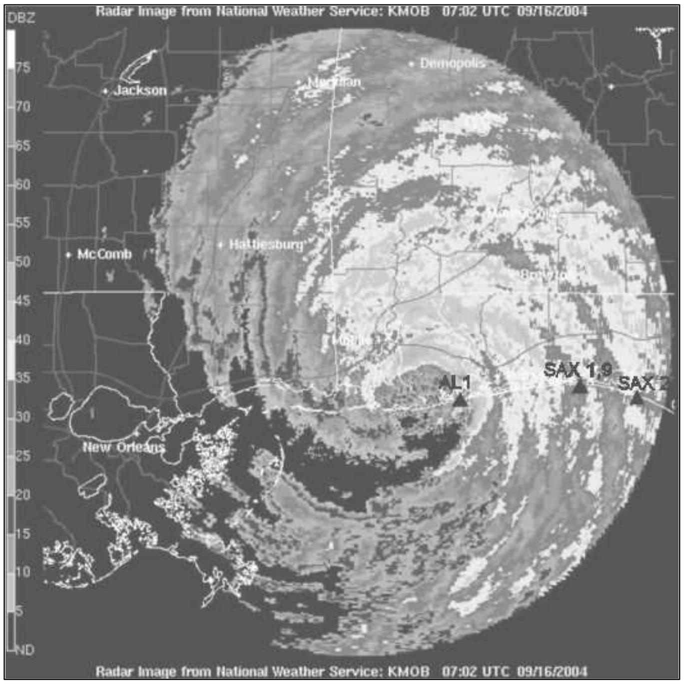

Figure 2 - Location of CHL-01 and SAX 1, 2, & 9 with Hurricane Ivan radar image at 0700 UTC 16/09/2004

Of the three nearshore stations only the single pressure gage at site 9 was recovered after Hurricane Ivan. The instrument was undamaged, but examination of the data showed a sudden change in mean depth at the peak of the storm indicated the gage had overturned, and damage to the fiberglass tripod verified that the mount had insufficient weight (about 200 lb of lead) to withstand the extreme wave loads. Fortunately, the tripod was later found by local fishermen some distance from its deployment station. Attempts to trigger the acoustic releases and searches by divers at Sites 1 and 2 were unsuccessful. Potential failure modes include displacement by the storm waves, burial by transported sediment, and/or failure of the acoustic release mechanism.

Programs with Incidental Missions

While other agencies and organizations monitor the coastal ocean, the COE Coastal and Hydraulics Laboratory (CHL) and the National Ocean and Atmospheric Agency (NOAA) National Data Buoy Center maintain the two largest and longest-lived observation networks. Most of the stations in the CHL Field Wave Gaging Program support site-specific climatology or coastal project performance studies [7]. Most of the stations in the NDBC Moored Buoy Program are maintained to provide operational support to the National Weather Service's forecast mission. While capture of data from these stations during hurricanes may be recognized as useful to the general oceanographic community, it is not the principal mission of the programs.

The Field Wave Gaging Program (FWGP): The Field Wave Gaging Program functions as an umbrella program to integrate and coordinate all COE wave data collection systems, regardless of funding source, into a cohesive network with uniform data management [8]. In November of 2001 CHL deployed a Civil Tek WW3D bottom mounted pressure array at Site AL1, about ½ nm offshore of Perdido Pass, FL in 8 m water depth. The array mount was a trawler-resistant tripod anchored to the seafloor by pilings. The system included a cable to an onshore interface that provided power and a telemetry link (via telephone line) for near-real time data capture.

When the cable was severed in January of 2004 the gage automatically went into "storm mode,' operating on internal batteries and storing measurements on internal memory. The gage had sufficient power and memory to continue to operate throughout 2004. Figure 2 shows the location of this gage and radar imagery of Hurricane Ivan as it came ashore on September 16, 2004. The gage was under the eyewall on the "strong side of the storm – a 'direct hit' by one of the most powerful hurricanes on record.

CHL bottom-mounted gages are normally deployed and recovered by divers. The COE made several attempts to recover the gage in the following year but were unsuccessful in locating the gage. On September 30, 2005 a non-government dive team successfully recovered the gage, but contracting issues delayed return of the data to CHL until July of 2007.

The Moored Buoy Program: National Data Buoy Center Station operates a large network of ocean platforms under the Moored Buoy Program that collect meteorological and oceanographic observations. In addition to their use in operational forecasting, warnings, and atmospheric models, moored buoy data are used for scientific and research programs, emergency response to chemical spills, legal proceedings, and engineering design [9]. Buoy types range from the 1.5-m-diameter coastal buoy to the 12-m-diameter discus 'monster' buoy. Data are typically collected and transmitted via GOES satellite hourly.

Station 42007 was a 3-m-diamter discus buoy deployed off of southeast Louisiana in 14 m nominal water depth. Figure 1 shows the relative position of 42007 and the hindcast wind field at 1500UTC when the eye of Hurricane Katrina was just ~ 45 nm due west.

Station 42035 was another 3-meter discus buoy also deployed in 14 m nominal water depth but off the Texas coast. Hurricane Rita tracked northwest across the Gulf of Mexico, making landfall about 0740 UTC on 24 September 2005. The closest point of approach to station 42035 was just 35 nm.

RESULTS

Hurricane Ivan

Site 9: Figure shows the time series plot of the wave parameters – significant wave height (H, in m) peak spectral period (Tp, in sec) and mean water depth (DEPTH, in m) - from Site 9 of the SAX04 Project. The gage failed some time after 0300 UTC on the 16th of September – about four hours before Ivan's landfall 60 nm to the west. Though it did not record the entire storm event, this gage might have captured the peak conditions at this site. The wave heights were still increasing but the surge level was actually decreasing. At Site 7, offshore from Site 9 in 83 m water depth, only slightly larger waves occurred at 0600 than 0300 [6].

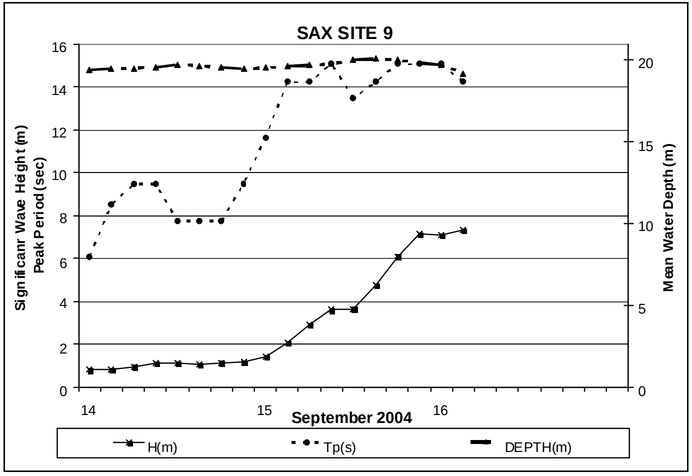

Figure 3 - Data from SAX Site 9 from 0000 UTC 14/09/2004 through 0300 UTC 16/09/2004

AL001: At the time of preparation of this paper CHL was still reviewing the data and it was not available for public release. A cursory inspection of the data by one of us[1] confirmed that the gage operated and recorded data during the landfall of Hurricane Ivan. At the peak of the storm significant wave heights were approximately 6 m and mean water depths were approximately 9 m, which places the gage effectively in the surf zone. Thus it is not surprising that the spectra displayed noise and instabilities during the hours immediately around landfall. Attribution of the cause of these problems is only speculative without access to the actual data, but an obvious issue is that the highly non-linear water surface profile and the aerated water column violate the basic linear assumptions relating instantaneous pressure at the seabed to surface elevation. Hopefully, post processing will permit recovery of a fully qualified, uninterrupted data set for this event.

Hurricanes Katrina and Rita

42007: Figure 4 plots the measured significant wave height and dominant period from station 42007 for August 28 and 29, 2005. The buoy ceased operation sometime after 0500 UTC, and was reported "damaged" by Forristall [1]. Wind speeds were below 35 knots as large, 14-sec swell began to exceed 5 m and approach from the south when the buoy failed.

42035: Figure 5 plots the measured wave height and period from station 42035 on September 23 and 24, 2005. While this buoy remained on station during the storm and the meteorological sensors functioned, there were quality control issues with the wave data during the closest point of approach of the storm. When wind speeds exceeded 40 kt and wave heights approached 5 m the wave sensor lost reliability.

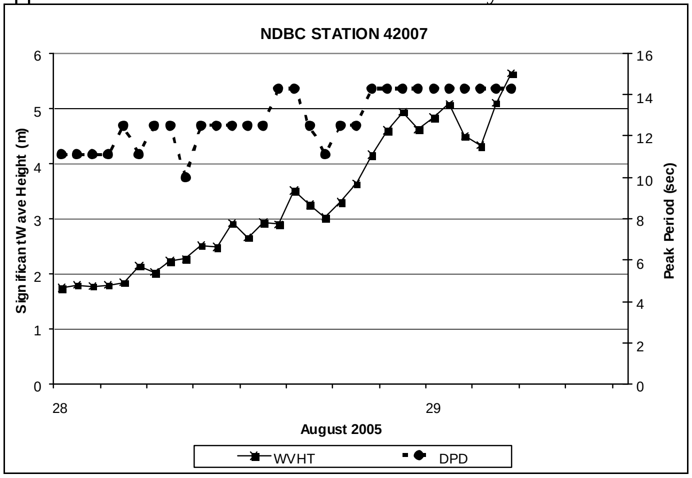

Figure 4 - Data from NDBC station 42007 from 0000 UTC 28/08/2005 through 1200 UTC 29/08/2005

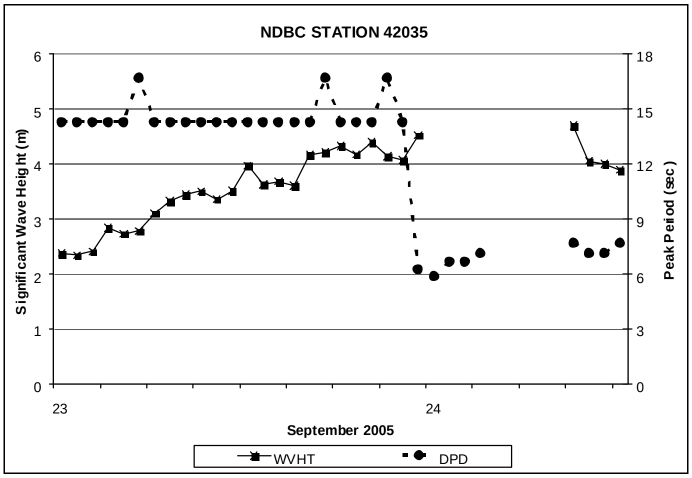

Figure 5 - Data from NDBC station 42007 from 0000 UTC 23/09/2005 through 1200 UTC 24/09/2005

Lake Pontchartrain Gages 22 and 23: Figures 6 is reproduced from the Draft Final Report of the Interagency Performance Evaluation Task Force [10]. It compares the measured significant wave height from the two miniature buoys with model results from STWAVE and SWAN. For purposes of this paper, the most interesting feature of Figure 6 is that both gages show a marked reduction in significant wave height when the wind field was strongest, and subsequent growth even as the wind field decreased. There is no physical rationale for reduction of the wave field at this time. Both the system

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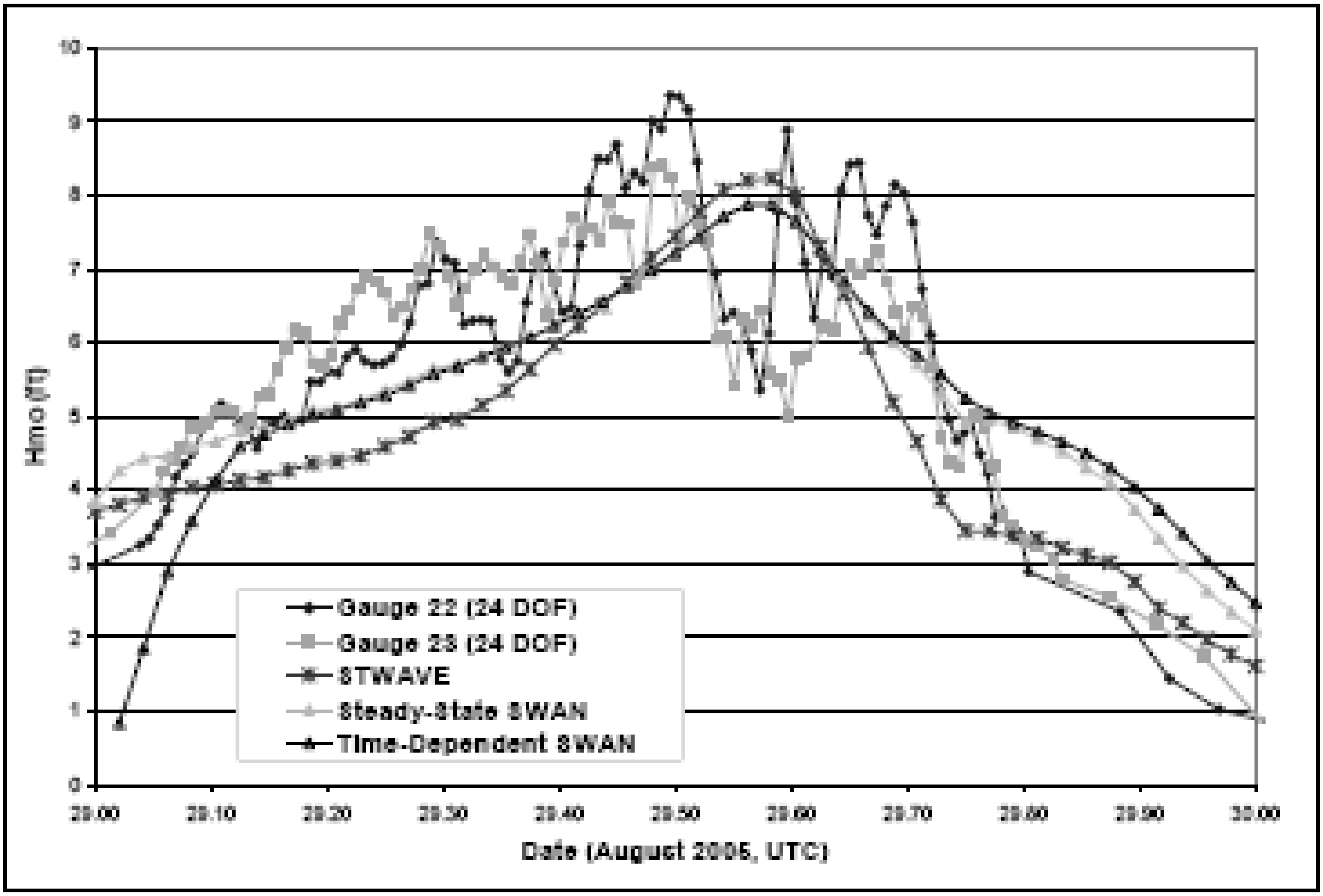

Figure 6 - Comparison of measured and modeled significant wave heights on Lake Pontchartrain for 29/08/200, from [10]

designer and the gage manufacturer concur that this interval of data is invalid due to temporary failure of the buoy-mooring system [11]. The consensus is that the buoys were flipped on their sides and stretched to the end of their mooring line by wind forces. Not only were the buoys unable to follow the water surface accurately because of the mooring dynamics, but the fixed accelerometers could not sense actual vertical displacement with the buoys pinned in this orientation.

DISCUSSION

Lessons

Of the 9 stations examined, none performed with complete reliability or accuracy under peak hurricane conditions. Five of the failures were related to inadequate platform, mount, or mooring performance, three were related to inadequate sensor performance, and two exhibited symptoms of both problems. It's important to note that neither the SAX40 gages nor the miniature buoys were specifically designed to withstand extreme wave conditions.

Obviously, increasing the weight of the pressure gage mounts would improve their stability. However, decades of experience with bottom-mounted sensors has proven that pile-supported platforms, as used by the CHL bottom-mounted gages, are more robust than simple gravity mounts. Not only do they resist episodic hydrodynamic and anthropogenic (e.g., bottom-trawls) loads more effectively, but they are less prone to chronic shifting due to scour of the supporting sediments.

The original design of the NSI miniature buoys utilized a discus flotation collar. The designers speculate that at extreme tilt angles, high velocity winds can penetrate under the disc and flip the buoy onto its side. One proposed improvement would be a more spherical flotation collar. However, this raises additional concerns with the buoy's surface-following characteristics under less extreme conditions.

A Conundrum

While the platform issue can be addressed through more robust design and better installation methods, the problem of the sensor/data analysis failures at peak conditions is less tractable. On one level, there is an inherent reliance on a linear transfer function between the sensor's output and the desired measurement in a highly non-linear environment. At a more basic level, our conceptual model of a progressive wave, with distinct interfaces between water and air above and water and seabed below, is hardly valid at the height of a hurricane in shallow water.

An Alternative

Measured extreme wave data is seldom used directly by the practicing engineer; rather it principally serves to validate numerical models. One field of endeavor with both large and widespread economic impacts is the forensic investigation of hurricane-damaged structures. Many of the residential and commercial structures affected by Hurricanes Katrina and Ivan were covered by separate insurance policies: one that covered losses due to wind damage only, and another that covered losses due to flood damage only. Identification – or in many cases the separation – of wind-induced damage and water-induced damage at each structure is of obvious concern to the insurance companies and the insured. As might be expected, difference of opinion on this issue frequently leads to litigation.

The purpose of a forensic investigation of these properties is to determine the time series of structural response to wind and hydraulic forces. The process of making this determination can be summarized as follows:

1. Run atmospheric hurricane model; generate wind filed time series
    ► Validate with measured atmospheric data
2. Run hydrodynamic circulation model; generate surge time series
    ► Validate with measured surge data
3. Run hydrodynamic wave model; generate wind wave time series
    ► Validate with measured wave data
4. Use predicted wind, surge, current, and wave time series to generate separate load time series
    ► Validate (?) with physical model results
5. Use predicted load to predict time series of structural response to wind and water
    ► Validate with laboratory results, usually steady state

The two weakest links in this process are determining the shallow water wave conditions and estimating the resulting wave loads. Wave models for a recently submerged, moving surf zone – exactly where the most affected, and often most expensive, structures can be found – are not quite state of the art; additional wave measurements in very shallow water are needed to improve these models. Propagation of shallow water waves through semi-submerged trees and structures – exactly where the majority of the damaged structures can be found - is still the state of tomorrow's art. Trust in this class of models will require measurements at normally upland sites that are inundated under hurricane conditions.

Current methodology for estimating wave forces treat non-breaking, already broken, and breaking wave conditions separately [12]. Peak nonbreaking wave forces on a non-porous vertical wall are estimated using the hydrostatic load of a head of water equal to the highest runup on the wall. Forces from already broken waves add a dynamic pressure plus a hydrodynamic pressure component. For forensic analysis, the most important case is the breaking wave force. Breaking waves impart very large pressure impulses (relative to the hydrostatic pressure). An empirical relationship is available for the peak impulse pressure, but wave-by wave variability is large [13].

Given the challenge of both obtaining and interpreting wave data under these extreme conditions, it's logical to consider leapfrogging the problem by measuring the hydrodynamic loads directly during a hurricane. Such a system should be sited where the hurricane damages occur (normally upland, densely developed regions) and produce a time series of vertical distribution of pressures and the total *load* on a structural member (while also collecting the atmospheric and hydrodynamic forcing time series). It may well be that the scatter in forcing is less than in the hydrodynamics. Perhaps a useful empirical relation between the most stable components - the wind field and surge level - and the resulting load would emerge, providing a "second opinion" to the 5-step process currently used.

CONCLUSIONS

The state of the art in collecting wave data in shallow water under hurricane conditions was examined using available data sets. Results from 9 different gages using different measurement approaches were examined for their performance during the two most devastating hurricanes seasons for the US in recent history. Both methods were partially successful in that some of each type operated during at least the approach of the hurricanes and useful data were eventually recovered. However each type failed to provide timely data and/or each exhibited instabilities or failure during the peak conditions. The closer the gage was to the storm's center and the shallower the water, the more likely it was to fail. If the data from the CHL1 gage during the peak of the storm passes quality control, it will be the single exception to this trend, and would represent the best benchmark for shallow water hydrodynamic models of hurricanes.

While recognizing and supporting the need for continued effort and research into improving this record, research into methods for obtaining measurements of structural loads directly is highly recommended. The load history on structures under hurricane conditions is an extremely valuable product that currently depends upon convoluted processing of the wave information. Direct measurement of loads may prove no more challenging to obtain and would be more directly applicable for many practicing engineers.

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REFERENCES

[1] Forristall, G. Z., 2007, “Comparing Hindcasts with Wave Measurements from Hurricanes Lili, Ivan, Katrina and Rita,” proceeding of 10TH International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, North Shore, Oahu, Hawaii, November 11-16, 2007

[2] McGehee, D. D., 1991, "Field Wave Gaging Program: Five-Year Gage Deployment Plan," Technical Report CERC-91-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS. Sept. 1991

[3] McGehee, D. D., and Earle, M., 2002, “Episodic Wave Data Capture with Miniaturized Instrumentation,” Proceedings, Oceans ’02, MTS/IEEE, Biloxi, MS, October, 2002

[4] Winer, Harley and McGehee, David, 2002, “A High-reliability System for Capturing Hurricane Wave Data,” Proceedings, Solution to Coastal Disasters 2002, ASCE, San Diego, CA, February, 2002

[5] McGehee, David D., 2005, “Data Report: Wave Conditions on Southern Lake Pontchartrain August 27 – September 5, 2005,” Contractor Report to the Coastal and Hydraulics Lab, US Army Engineer Research and Development Center, Emerald Ocean Engineering LLC, Pensacola, FL, September, 2005.

[6] Herbers, T. H.C., O’Reilly, W. C., and Ardhuin, F., 2005, “Wave Measurement and Predictions During SAX04,”May, 2005

[7] McGehee, D. 1991. "Field Wave Gaging Program: Five-Year Gage Deployment Plan," Technical Report CERC-91-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS. Sept. 1991.

[8] McGehee, D. 1991. "Management of the Field Wave Gaging Program Data Base," CETN I-46, US Army Engineer Waterways Experiment Station, Vicksburg, MS, Dec. 1991.

[9] ______, “Moored Buoy Program,” online at http://www.ndbc.noaa.gov/mooredbuoy.shtml, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, National Data Buoy Center, Stennis Space Center, MS

[10] ______, 2006, “Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System,” Draft Final Report of the Interagency Performance Evaluation Task Force Volume IV – The Storm, US Army Corps of Engineers, Washington, DC, 1 June 2006

[11] McGehee, D. D., Winer, H., Earle, M., Smith, R., Mesa, C., Pollock, C., Hughes, B., 2006, “Measured Wind Waves in Lake Pontchartrain During Hurricane Katrina,” 2006 Ocean Sciences Meeting, ASLO/TOS/AGU, 20-24 February 2006, Honolulu, HI

[12] Tung, C.C., Kasal, B., Rogers, S.M., and Yeh, S.C., 1999, “Behavior of Breakaway Wall Subjected to Wave Forces: Analytical and Experimental Studies,” Federal Emergency Management Agency, Washington, DC, February 2, 1999

[13] Schmidt, R., Oumeraci, H., and Partenscky, H. W., 1992, “Impact Loads Induced by Plunging Breakers on Vertical Structures,” 23rd International Coastal Engineering Conference, American Society of Civil Engineers New Your, NY