WAVE-INDUCED SURGES DURING HURRICANE OPAL

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1. INTRODUCTION

Hurricanes storm surges and waves at the coastline have been the cause of damages in the coastal zone. On the U.S. Gulf Coast, for example, Hurricane Opal (1995) made landfall near the time of low tide and resulted in severe flooding by storm surges and waves. Storm surge can penetrate miles inland from the coast. Waves ride above the surge levels, causing wave runup and mean water level set-up. These wave effects are significant near the landfall area and are affected by the process that hurricane approaches the coastline.

During 1950-1977, hurricane wave models based on significant wave height and period were developed (e.g. Bretschneider, 1957; Ross, 1976) for marine weather prediction and offshore oil industry design. Cardone (1976) employed a spectral wave model for diagnostic hurricane studies. In the 1990's, advances in computer have enabled the development of global ocean wind wave prediction models. For engineering applications, Hsu et al. (2000) demonstrated that the U.S. Army's hurricane wave prediction method (USACE) is still adequate in coastal wave applications. The merit of an ocean wave model is that it can be used to learn tropical cyclone wave behavior. Based on a numerical solution of the radiative transfer balance equation and limited field data collected during two tropical cyclones on Australia's Northwest Shelf, Young (1988) proposed a parametric hurricane wave model. The model captures the physics of tropical cyclone waves via the JONSWAP formulation of wave spectrum. The model is forced by the surface wind beneath the moving storm and prescribes maximum wave height and period, which is the severe swell wave generated by the storm. The Army Corps of Engineers has adopted his formulation and a monogram in the Coastal Engineering manual.

In the present approach, we integrated maximum surface winds with Young's wave model and obtained hurricane waves. The model is extended to coastal marine zone by using Hsu's formula. The obtained coastal waves are transformed in the near shore to calculate the wave induced set-up and run-up. To demonstrate the modeling results, the model is applied to Panama City Beach during Hurricane Opal.

2. MODEL FORMULATION

The hurricane surface wind field has been investigated for storm surge and wave problem. Atkinson and Holliday (1977) developed a simple formula relating the cyclone's pressure drop to maximum sustained wind for the Western Pacific. A more general form was proposed by Holland (1980). The merit of these models is that they are analytical models for the surface wind profile in a hurricane. A similar formulation was applied to the wave model in the present work. The framework of the hurricane wave model is described below.

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2.1 HURRICANE WIND AND STORM SURGES

Holland (1980) employed a standard pressure profile for a tropical cyclone and obtained the popular gradient wind profile. Jelesnianski and Taylor (1976) assumed a surface wind profile in the pressure equation. Their wind profile is normalized by the maximum wind speed in a concentric circular pattern. The radius to the maximum wind, R_{max}, defines the location of the maximum wind speed $V_{max.}$ This model has been applied to the U.S. National Weather Service's tropical storm surge model. It is conveniently named as the SLOSH wind. The radius of maximum wind, R_{max}, can be estimated from aircraft reconnaissance or satellite image as suggested by Hsu and Yan (1998). The surface analysis wind developed by Hurricane Research Division of NOAA can also be used for determining it. The storm surge data used here is the output of SLOSH simulation. It should be noted, for hurricanes, the highest water levels are rarely captured by tide gages. Modelers frequently refer to field survey such as high water marks. High water marks found inside inundated buildings are good indicators of still water levels. Marks outside buildings show wave actions. Debris lines show the upper limit of wave swash. The mean water level is composed mainly of astronomical tide, storm surge, and wave set-up. The hurricane winds drive the storm surge as well as the waves. The wave set-up is produced by the breaking waves. The amount of wave set-up can easily amount for as much as 2 to 5 ft, depends upon the beach slope. The total mean water level is recorded by the tide gauge, and the debris line shows the maximum limit of swash waves impinging on the beaches.

As storm surge modeling experienced, the 10 minutes sustained wind is used for wave modeling. Both the USACE winds and SLOSH winds solely depend on the values of storm intensity, storm size and forward speed. For present applications, we included both the USACE wind method and SLOSH winds in the determination of the maximum wind to cater various hurricane conditions. The accuracy of the maximum wind speed is critical for maximum wave and storm surge calculations.

2.2 HURRICANE WAVE MODEL

Young (1988) developed the wave model based on the 2nd generation of WAM model using nested grids with a finest resolution of 15-km. The model produced data and then calibrated with field measurement of storm waves. The model analysis focuses on the maximum wave height and period. By satisfying wave growth and wave dispersion criteria, fifteen empirical coefficients are determined. The parametric wave model calculates an equivalent fetch based on the radius of maximum wind and the forward storm speed. The method of solution applies smoothly to a range of tropical cyclone conditions in Australia. Wu (2003) has shown that it gives a good estimate of maximum significant wave height and peak period (see Table 1) compared with various observations.

Coastal Wave Modeling :

In shallow water, research on source terms that wind wave modeling requires is still on-going. For swell wave, shoaling-refraction and breaking is the dominant process, the waves are depth controlled near the shore. We adopted Hsu et al. (2000)'s wave height decay formula and Kweon and Goda (1996)'s breaking wave model with an extension to random wave set-up. The wave run up is best described by Mase (1989). These formulas have been tested for natural beaches with field data. In general, the model indicates that wave set-up is gradually increasing as the beach slope becomes steeper and the wave steepness gets higher value.

3. WAVE MODEL VERIFICATION

To verify the validity of the formulation introduced in Section 2, we applied the parametric model to hurricane cases that occurred along the U.S. East Coast and the Gulf of Mexico. The hurricanes were chosen such that the NOAA buoys were to the right front of the hurricane track, then the wind and wave data were collected for model comparison. Through the 1990's, only six hurricanes (Table 1) were found. The parametric wave model effectively calculated the significant wave heights and periods at the buoy sites.

Hurricane Floyd cost billion's of dollars of damage to the State's heavily developed coast when hurricane made landfall. Buoy station 41010 captured increasing wave heights as Floyd made a northward turn parallel to the northeast coast of Florida.

Table 1 summarizes the comparisons of predicted waves and observed wave data. For Hurricane Bonnie, the input data are from the NOAA research aircraft by Wright et al. (2001), in which the maximum wave height was 10.70 m with a period of 13.89 sec (based on a wavelength of 300 meters). The model calculates a significant wave height of 10.46 m and wave period of 13.78 sec. The overall accuracy of wave period prediction is as good as that of the wave heights. The mean relative error (MRE) for the six cases is less than 5 percent of the corresponding cases.

The parametric wave model is easy to use but limited to linearly varying tropical cyclone paths. It is meant to complement the operational ocean hurricane wave model. An ocean spectral wave model with highly nested grids (to capture the maximum peak wind) may yield a solution with the same degree of accuracy as the parametric model at the expense of extensive computer calculations. Using the same hurricane information, the present model can effectively estimate the probable peak wave during the storm. We tested many other hurricane seas and found that the simple formula by Hsu (1991) does represent an upper bound of the maximum wave with about 20-50% error. However, the present approach can give accurate values for various hurricane cases, as long as input data are correct.

Table 1. Comparisons of significant wave heights and periods to observed values for U.S. hurricanes.

Hurricanes track time (UTC)		Fran 09/05/96 21Z	Lili 10/02/02 2030Z	Georges 09/27/98 16Z	Floyd 09/15/99 08Z	Bonnie 08/24/98 21Z	Iniki 09/11/92 18Z
Wave Height (m)	Model	11.50	11.12	10.48	14.24	10.46	4.95
	Data	11.64	11.20	10.88	14.20	10.70	5.05
Period (s)	Model	14.22	13.28	13.8	14.95	13.8	9.0
	Data	14.29	13.25	13.2	15.4	13.9	8.4
Relative Error (%) for wave height		-1.2	4.5	3.6	.28	-2.2	-2.0

4. WAVES AND SURGES FOR HURRICANE OPAL

Hurricane Opal (1995) made landfall at Pensacola, FL. The observed post-storm high water marks indicate strong wave action on the beaches to the right of landfall, at the distance of the radius of maximum wind. The maximum storm surge observed by a tide gauge at Panama City Beach is 8.0 ft. The SLOSH computes maximum storm surge of 8.7 ft. A few outside high water marks were collected at 10-12 ft above mean sea level. Several debris marks were observed at 18 ~21 ft.

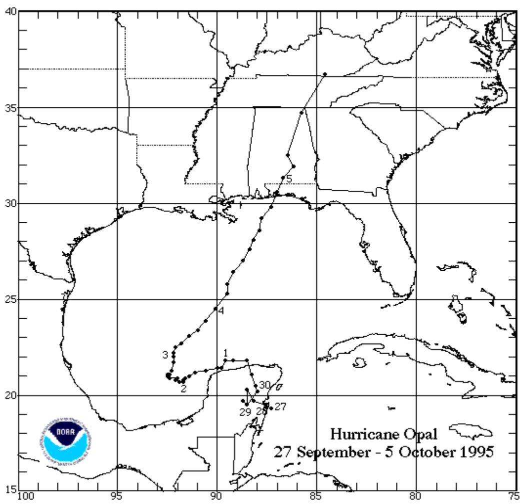

Figure 1: Date and time of Hurricane Opal track.

The hurricane wave model was run along the track and yields highest wave 48.6 ft (14.8 m) when the center pressure is the lowest (916 mb) on 1200Z, Oct 4. After that time, the maximum wave is reducing in magnitude. The wave height decreases as Opal near the coast. The coastal wave height at 25 ft water is increasing as the storm approaches the coast, and it reaches its maximum value at 31.5 ft (9.6 m) one hour prior to landfall (2200Z, Oct 4), while the storm surges reach the peak value right at the landfall. The calculated storm surges by the SLOSH increase the elevation much faster than the mildly rising waves at the Beach (Fig. 2).

The breaking wave model was applied for wave decay and the computation of mean water levels. The wave breaks continuously across the coast and causes the maximum wave set-up of 2.8 ft along the peak surge. The waves are saturated prior to landfall. However the maximum wave set-up is not occurred at the shoreline but hundred meters inland. It is assumed to add the wave run-up above the storm surge value to show the limit of wave motion. At landfall (Fig. 3), the calculated maximum wave run-up is 10.8 ft, resulting in a total elevation of 18.8 ft above the measured mean sea level, which is in good agreement with the observed debris line elevation of 18.0 ft.

5. CONCLUSION AND DISCUSSIONS

The complexity of high winds near the eye center requires a numerical model with high resolution both in time (hourly) and in space (1 km). A parametric wave model derived from numerical solutions of a nested grid ocean wave model and field data is applied, and the modeling results for hurricane Opal are summarized:

(1) For six major hurricanes in the U.S. East Coast and the Gulf of Mexico, the parametric model gives wave height predictions within 5% error compared with the measured buoy wave data. The wave period and thus wave steepness are also favorably verified with the wave data offshore and inshore.

(2) The parametric model was tested for a series of wind and storm conditions. It covers more than the formula in Hsu (2000), which simply relates the wave height to the central pressure drop. For a wide variety of applications, the present model can work with a hurricane track model to make real-time high seas forecast.

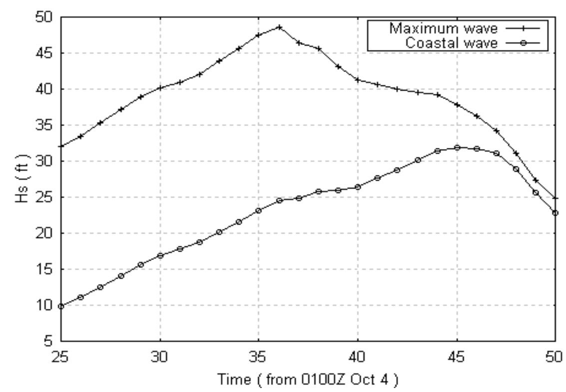

Figure 2: Calculated maximum significant wave heights and coastal wave heights at the Panama City Beach during Hurricane Opal (1995). Landfall time is at hour 46.

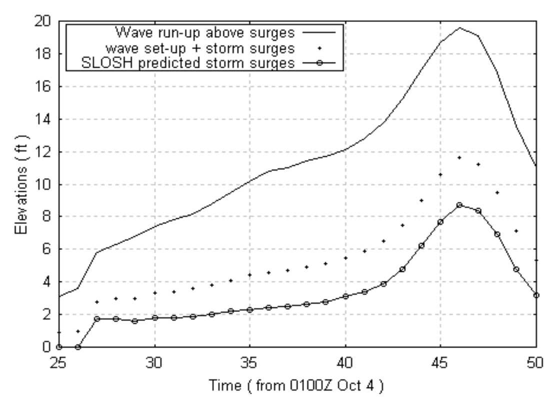

Figure 3: Water level elevations at Panama City Beach, landfall time is at hour 46.

(3) Field observations over the ocean are extremely sparse during a hurricane. NOAA scientists recently installed radar on the aircraft P3 to measure the wave

spectrum field during hurricane motion. They developed an empirical method of predicting dominate swell wave direction. This information can be used with a coastal wave model for modeling coastal flooding.

(4) Hurricane wave modeling requires information on the hurricane wind field and the hurricane track. The computed waves are sensitive to the storm intensity and storm speed. A two dimensional numerical modeling of coastal waves and storm surges is still incomplete, thus a parametric model is applied for evaluation of the relative role of wave set-up and storm surges and run-up. It is concluded that the inland flooding is the combined result of a high storm surge elevating the water level on a mild beach slope, causing wave breaking process further inland and swash a high wave run-up on the beach. Without storm surges elevation, the wave set-up is limited and wave run-up is mostly confined on the foreshore slope.

(5) The present results are slightly over estimated, it may be caused by less wave height dissipation in the shallow water. The coastal wave calculations rely on the distance of beach location to the storm center, which implies the water depths. But, Hsu's formula involves the storm size, which makes the calculations failed once the storm is inland and the fetch is shorten drastically.

For an evaluation of wave effects along the coastline, a two-dimensional multiple-nested ocean wave model driven by a nested hurricane wind field is preferred. Likewise, a nested storm surge model would be desired to couple the waves from deep to shallow waters. The solution of hurricane wave forecasting is still wanted, thus observations of waves at the coasts are required for monitoring and model verification.

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