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Short Communication

An improved empirical equation for storm surge hydrographs in the Gulf of Mexico, U.S.A

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ABSTRACT

Traditional storm surge hydrograph equations are practically unable to fit well with the falling limb of the observed storm surge hydrograph. This study has investigated storm surge hydrographs induced by Categories 3 and 4 hurricanes at several NOAA coastal stations in the Gulf of Mexico. Five observed storm surge hydrographs for Category-3 hurricanes and four observed hydrographs for Category 4 hurricanes are chosen accordingly in the investigation. The observed storm surge hydrographs are obtained by subtracting tidal harmonic signals from the observed water level hydrographs. Comparisons of the average observations and the existing synthetic hydrograph show that the Categories 3 and 4 storm surge hydrographs do not follow the same trend. Existing synthetic empirical equations are found unable to fit well with the observed storm surge hydrographs. Due to the simple parameterization of the existing synthetic hydrograph equations, an improved empirical equation for general storm surge hydrograph is proposed in this study. Based on the observed data, a full set of parameters of the proposed equation for Categories 3 and 4 hurricanes is estimated. The improved empirical equation fits well with the observations of the storm surge hydrographs on both rising and falling limbs.

1. Introduction

The US Coastal areas are threatened by the risk of damages due to storm waves and storm surges (Wamsley et al., 2010; Cheung et al., 2003). In the coastal states of the Gulf of Mexico, hurricane generated storm surge is the major cause for extreme floods. On September 16th, 2004, storm surge associated with Hurricane Ivan knocked 58 spans off the eastbound and westbound of the Escambia Bay Bridge and caused heavy beach erosions in Pensacola, Florida. In 2005, Hurricane Katrina was the third most intense hurricane with the fourth lowest central pressure recorded at landfall in the US. It brought a 9.2-m storm surge to Biloxi, Mississippi, which is the highest ever observed in North America. As a Category 3 hurricane during the landfall, the storm surge of Katrina breached the levee system that protected New Orleans. In addition to inundations, strong currents induced by storm surges can also cause strong sediment scours around bridge piers, which may affect the safety of the bridges in coastal and estuarine waters (Sheppard and Miller, 2003). In flood mapping and bridge scour analysis in estuaries and bays for coastal hazard mitigation and management, numerical modeling studies often require storm surge hydrographs in coastal areas as boundary conditions (Kriebel and Dean, 1984; Sheppard, 1997; Chen et al., 2007). When observed storm surge hydrographs are not available, synthetic storm surge hydrographs are usually specified as boundary conditions based on the design storm surge elevations (Sheppard and Miller, 2003). Therefore, adequate descriptions of storm surge hydrograph are important to coastal flood studies.

Some studies (e.g. Ebersole et al., 2010; Bunya et al., 2010; Dietsche et al., 2007) indicate that storm surge hydrographs for different hurricanes may be different. Considering that Categories 3 and 4 hurricanes in the Gulf of Mexico often cause major damages to the region, major objectives of this study are to investigate the characteristics of the storm surge hydrographs by analyzing observed data, validating existing empirical storm surge hydrographs by comparing to observations, and improving the empirical hydrograph for better descriptions of storm surges induced by Categories 3 and 4 hurricanes in the Gulf of Mexico.

2. Literature review

Previous studies (Cialone et al., 1993; Edge et al., 1998; Sheppard and Pritsivelis, 1999) describes a basic equation for synthetic storm surge based on the atmospheric pressure distribution, hurricane forward speed, hurricane radius of maximum wind,

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and maximum surge level. Because the pressure is assumed to vary radically from the hurricane eye, the resulting surge hydrograph is symmetrical before and after the time of the peak surge elevation. Zevenbergen et al., 2002 selected two largest events at nine model stations equally spaced along the coast from Miami, Florida to Machias, Maine, and evaluated the synthetic storm surge hydrograph by reviewing hydrodynamic model stations along the Atlantic coast to determine if there was any consistency in the hydrograph shapes. If a particular hurricane would have been included more than twice in the overall data set (i.e. appearing at more than two stations), then the third highest water level was selected in its place. Based on the criteria, the use of the third highest water level was required at only two of the nine stations. Zevenbergen et al. (2002) presented an alternative equation for the falling limb of the storm surge hydrograph, by adding a term to the basic equation to match the mean falling limb. Either the observed water levels or the synthetic hydrograph can be used as the water level boundary conditions in hydrodynamic numerical simulation. Zevenbergen et al. (2002) has normalized the hydrographs by dividing the surge hydrograph by the peak surge for that event and location. Their results indicate that storm surge hydrographs have a tendency for steep falling limbs and frequently drop below the mean sea level datum. The mean hydrograph illustrates that the falling limb is, on average, twice as steep as the rising limb.

Overton et al. (1999) conducted a study of storm surge hydrograph boundary condition in North Carolina, and developed a damped sine wave function. The approach is purely empirical based on a nonlinear regression analysis via the Levenberg–Marquardt method, with four parameters to be fit by the regression. Candidate parameters sets were obtained at each station by eliminating parameters which produced correlation coefficients less than 0.75. Candidate parameter sets were roughly grouped together based on the similar shapes exhibition of many adjacent hydrographs, which finally led to the selection of four "characteristic" curves by comparing synthetic and predicted hydrographs. The four "characteristic" curves provide a better fit to the predominant shape.

There are only limited studies of the storm surge hydrograph in the Gulf of Mexico, where it is vulnerable to tremendous severe hurricanes (e.g. Sheppard and Pritsivelis, 1999; Xu and Huang, 2008). Xu and Huang (2008) conducted a hydrodynamic modeling study of storm surge for Hurricane Ivan in Pensacola Bay with a basic synthetic storm surge hydrograph specified in the tidal boundary. Comparison with observations indicates that the falling limb of the synthetic hydrograph does not match the observations. There are similar observations in other stations along the Gulf of Mexico, which can be used to provide good validations for existing methods for storm surge hydrograph. Considering that storm surge hydrographs induced by different category hurricanes have not been fully investigated in previous studies, the characteristics of storm surge hydrographs for Categories 3 and 4 hurricanes in Gulf of Mexico are presented in this study.

3. Hurricane tracks in the Gulf of Mexico

The available combined storm surge (storm surge and harmonic tides) hydrographs are obtained from the Atlantic Tropical Storm Tracking by each year on the website (http://weather.unisys.com/hurricane/atlantic/index.html). The Gulf of Mexico is vulnerable to major hurricanes (Category 3 and above) with some devastating hurricanes landing in recent years, such as Hurricane Katrina and Dennis in 2005. To study the corresponding hydrographs for Categories 3 and 4 hurricanes, the chosen hurricanes and the landing stations are listed in Tables 1 and 2. The tracks of selected hurricanes are shown in (Fig. 1). The station near the hurricane passing track in the coastal areas during each chosen hurricane is selected for the study. For instance, Hurricane Katrina (2005), the most impacted station, Station Pilots, is chosen. Four Category 4 hurricanes are selected in this study. Actually, there are more hurricanes in Categories 3 or 4. For instance, the hurricane Atlantic-Gulf of 1919 and the hurricane Carla of 1961 are in Categories 3 and 4 correspondingly. However, they are not selected because data available in stations during the hurricanes are too far from the landing site, which are not fit for the storm surge hydrograph analysis. Thus, total eleven storm surge cases are chosen for this study with five from Category 3 hurricanes and four from Category 4 hurricanes (as shown in Tables 1 and 2). The observed hydrographs combining storm surge and astronomical tides at the specific station during the corresponding hurricane are obtained from NOAA website.

Table 1
Selected Category 3 hurricanes and corresponding stations in the Gulf of Mexico.

No	Year	Name	Studied station
1	2005	Rita	Port Fourchon
2	2004	Ivan	Orange Beach
3	1999	Bret	Corpus Christi
4	1995	Opal	Panama City
5	1992	Andrew	Grand Isle, LA

Table 2
Selected Category 4 hurricanes and corresponding stations in the Gulf of Mexico.

No	Year	Name	Studied station
1	2005	Dennis	Panama City
2	2005	Katrina	Pilots
3	2004	Charley	Port Manatee
4	1957	Audrey	Galvestonpier21

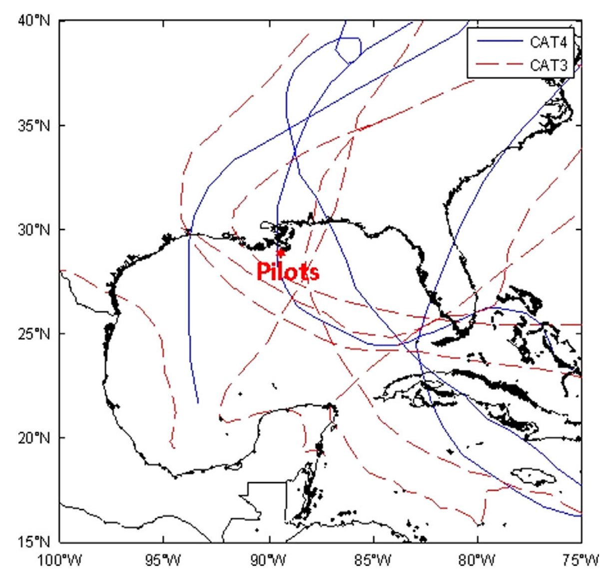

Fig. 1. Tracks of selected hurricanes.

4. Storm surge hydrographs after removing tidal signals from harmonic analysis

The water level measurements from NOAA coastal observed stations are the random combinations of storm surge and