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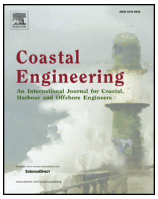

Estimating extreme sea levels in Yangtze Estuary by quadrature Joint Probability Optimal Sampling Method

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ABSTRACT

Effective estimation of extreme sea levels is of primary importance for coastal construction and coastal hazard mitigation. To predict 100-year and 200-year Annual Maximum Water Levels in Yangtze Estuary, simulation studies using the Quadrature Joint Probability Method-Optimal Sampling (JPM−OS−Q) to generate a set of optimal synthetic typhoons and river discharges combined with numerical hydrodynamic models capable of accurately simulating sea levels were conducted. During the synthetic simulation combination generation process, astronomical tide was also taken into account based on the Monte Carlo method. After a series of model validations, which showed that this model performed well to reflect the characteristics of the typhoon field, wave height, and sea level in the studied region, this model was implemented to predict extreme sea levels. Through simulation, 100-year and 200-year Annual Maximum Water Levels at Wusong station were predicted to be +6.08 m (Wusong Datum, WD) and +6.28 m WD, respectively, while these two values for Baozhen station were predicted to be +6.12 m WD and +6.33 m WD, respectively. Also, the 100-year and 200-year Annual Maximum Water Levels at Hengsha station were predicted to be +5.99 m WD and +6.13 m WD, respectively. Comparisons with former studies showed that the JPM−OS−Q method can be used to forecast extreme sea levels during typhoons in Yangtze Estuary. Estimating results from this study would be conducive to risk assessment in coastal areas as a reference.

1. Introduction

Extreme sea levels caused by typhoon-induced storm surge can wreak havoc in coastal regions such as Yangtze Estuary. Such potentially damaging hazards can bring about severe destruction to coastal defenses and result in wave overtopping, seawall submersion as well as inland flooding, thus causing devastating socio-economic impacts on vulnerable and exposed society (Sun et al. (2015); Chen et al. (2007); Du et al. (2010)). Storm surge risk has always been an issue concerned by various governments and scholars. However, although existing technology is increasingly effective at predicting storm surge with specific storm conditions (Shroder et al. (2015)), and massive flood protection engineering has been constructed, exposed population and economic resources located in low-lying coasts are still highly vulnerable to storm surge. Among all marine disasters, storm surge disasters ranked first in China in terms of direct economic loss, accounting for an average 90.75% of the total loss from 2000 to 2016 (State Oceanic Administration (State Oceanic Administration, 2016)). Recent storm surge disasters induced by Katrina (2005) and Haiyan (2013) are also reminders of this vulnerability (Aerts et al. (2014)). As one of the deadliest hurricanes in the twentieth century, Hurricane Katrina generated a maximum storm surge of 8.50 m. The large storm surge caused the catastrophic failure of several levees and floodwalls that protected New Orleans; about 80% of New Orleans was flooded and 1833 people died as a result (Knabb et al. (2006)). Typhoon Haiyan, another extraordinarily powerful and deadly typhoon, resulted in a maximum storm surge of 7.00 m in the city of Tacloban and left 6293 individuals dead (Takagi et al. (2015)). Additionally, as seas level rise and the number of population and value of assets increase in the potentially dangerous coastal region due to socioeconomic development, together with massive investments in flood defenses have been proved inadequate (Zhou et al. (2016)), it's undeniable that coastal populations and assets are becoming more vulnerable to extreme flooding from typhoons (Michel-Kerjan and Kunreuther (2011); Woodruff et al. (2013); Muis et al. (2016); Yin et al. (2017); Yang et al. (2015)). Under exposed conditions, higher levels of vulnerability and increased

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populations and assets may increase the storm surge risk with the same typhoon conditions. In this context, coastal seawalls and flood-control levees must be constructed or upgraded to combat storm surge risk. In order to better inform decision-makers about the design of coastal structures, disaster prevention, and mitigation agencies, there is an urgent need to accurately estimate extreme sea levels for given design return periods. Such estimations are a central component of coastal flood hazard studies and have been extensively investigated (Arns et al. (2013); Sobey (2005); Haigh et al. (2010); Huang et al. (2008); Xu et al. (2014a); Xu and Huang (2011); Wang et al. (2012); Mazas et al. (2014)).

There have been two main approaches to this task: frequency analysis and hydrodynamic modeling. Based on regional historical observed water level dataset, frequency analysis is usually conducted by using one of many well-known distribution types, such as generalized extreme value (GEV) distribution, to estimate extreme sea levels. This approach is generally simpler and more cost effective in comparison to the hydrodynamic modeling method (Huang et al. (2008)). However, availability of long-period datasets is of critical importance to the accuracy of frequency analysis, this method is highly sensitive to the sampling uncertainties that exists in short-period datasets (Xu and Huang (2011)). Application of the frequency analysis method is limited by insufficient numbers of tide gauges or record lengths available to reliably estimate extreme sea levels; this limitation is particularly apparent for developing countries. Unlike frequency analysis, hydrodynamic modeling employs temporal and spatial varying wind and pressure fields coupled with a hydrodynamic model to simulate storm surge process. A few methods for simulating extreme water sea levels exist, such as the Empirical Simulation Technique (EST) (Scheffner et al. (1996)), Monte Carlo (Dean et al. (1995)) and Joint Probability Method (JPM) (Myers (1970)). Of these three modeling methods, the JPM method has the conceptual advantage for considering all possible combinations of typhoon characteristics consistent with the local climatology, each weighted by its appropriate rate of occurrence (Toro et al. (2010a)). It is only limited by the accuracy of the estimated parameter distributions. Numerous previous studies have shown that the most appropriate method for estimating extreme sea levels is JPM (Toro et al. (2010a); Toro et al. (2010b); Resio et al. (2009); Divoky and Resio (2007)).

Although the JPM approach is preferred among all methods, the traditional JPM approach indeed imposes a heavy computational burden on the analysis. Therefore, increasing attention has been paid to the Joint Probability Optimal Sampling Method (JPM-OS), which aims to reduce computational burden while maintaining accuracy compared to the traditional JPM approach (Toro et al. (2010a)). Resio (2007) provided an optimal sampling scheme based on the response surface method. On the basis of using a moderate number of synthetic storms, as applied in the Louisiana study, this scheme interpolates between the calculated surge elevation (in five dimensions) to obtain the surge elevation for any desired combination of parameters. Unlike the response surface method, Toro et al. (2010b) developed a different integration scheme called the quadrature method, which had been applied in the post-Katrina study of coastal Mississippi. This scheme employs an algorithm proposed by Powell (2004a) to select finite parameter combinations as a representative set of synthetic storms and assign an appropriate weight to each synthetic storm. In this way, the JPM multi-dimensional integral is transformed into a weighted summation that permits the reduction of computational burden. In the meantime, Toro et al. (2010a) provided a detailed comparison of estimating results from the response surface method and the quadrature JPM-OS method for the coast of Mississippi. Results indicate that both quadrature and response surface methods are capable of easing the computational burden with very little loss of simulating accuracy. Meanwhile, nearly identical results are given by these two approaches. Aside from quadrature JPM-OS and response surface JPM-OS, another optimized method was presented by (Condon and Peter Sheng (Condon and Peter Sheng, 2012)) for determination of inundation return frequencies. This method is implemented by using piecewise multivariate regression splines coupled with dimension adaptive sparse grids. Although all of the above options are valid, due to its more readily automated feature (FEMA (FEMA, 2012)) and the successful experiences in the surge studies of Mississippi (Toro (2008)), the coast of New Jersey (excluding Delaware Bay), and portions of New York (FEMA (FEMA, 2014)), the quadrature JPM-OS method has been recommended by the Federal Emergency Management Agency (FEMA) for the estimation of storm surge elevation frequencies (FEMA (FEMA, 2012)).

From what has been reviewed above, the quadrature JPM-OS method is selected as the final choice to overcome the lack of long-term observed water level data and to conveniently predict accurate extreme sea levels for given design return periods. However, in previous studies related to the application of the quadrature JPM-OS method, only typhoon parameters and astronomical tide are tackled. Another important variable, river discharge, has not been included in the improved method. This is maybe due to the specific characteristics of those study areas. Nevertheless, it is noteworthy that the river discharge is a critical influencing factor that affects surge generation in some estuary regions (Martyr et al. (2013); Svensson and Jones (2002); Dube et al. (1986)). Ignoring the interaction between typhoon storm surge and river discharge may lead to the underestimation of extreme sea levels in the coastal zone. Therefore, extra effort is needed to improve the estimation precision by taking the variable of river discharge into consideration. The primary objective of this paper is to estimate extreme sea levels in Yangtze Estuary, which is accomplished through the use of quadrature JPM-OS method and Delft3D-FLOW hydrodynamic model. The river discharge and four typhoon parameters (pressure deficit, forward speed, typhoon heading and distance to coastal reference point) are invoked as JPM-OS parameters; meanwhile, the effect of astronomical tide is also taken into account. The results from this study will provide a useful reference for assessing hazard in coastal areas and coastal construction.

2. Study area

As one of the world's largest alluvial estuaries, the Yangtze Estuary is of great ecological and socio-economic significance since one of the most developed Chinese economic zones is located in its vicinity. Taking Shanghai as an example, this city covers a total area of 6340.5 square kilometers and has a high population density of 3809 persons per square kilometers in 2015 due to a large number of migrants. It produces 3.9% of the national gross domestic product with only 0.06% of the country's territory and 1.8% of total population in 2015 (Shanghai Municipal Statistics Bureau and Survey Office of the National Bureau of Statistics in Shanghai (Shanghai Municipal Statistics BureauSurvey Office of the National Bureau of Statistics in Shanghai, 2016); National Bureau of Statistics of China (National Bureau of Statistics of China, 2016)). The dense population and rapid economic development results in the high vulnerability of this area due to natural hazards. Meanwhile, due to its specific location, the Yangtze Estuary is inevitably subjected to a number of typhoons and associated storm surge disasters almost every year (Xu and Huang (2011); Chen et al. (2001); Wang et al. (2011)). Historical storm surge disasters induced by typhoon Wanda (1956), typhoon Winnie (1997), typhoon Matsa (2005) and typhoon Khanum (2005) all had resulted in severe social and economic loss in this region. Taking typhoon Winnie (1997) as an example, this typhoon had led to one of the most serious storm surge hazards in the Yangtze Estuary. It was confirmed that 186 people had been killed and the damage exceeded 22.9 billion yuan in the Zhejiang province, Jiangsu province, and Shanghai (State Oceanic Administration (State Oceanic Administration, 1997)). During the period from 1984 to 2009, the total number of casualties related to typhoons was 448 in Shanghai, with 54 people killed and 394 people injured (Shi and Cui (2012)). Hence, the potential danger from extreme sea levels