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Numerical simulation of typhoon-induced storm surge along Jiangsu coast, Part II: Calculation of storm surge

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Abstract

The Jiangsu coastal area is located in central-eastern China and is well known for complicated dynamics with large-scale radial sand ridge systems. It is therefore a challenge to simulate typhoon-induced storm surges in this area. In this study, a two-dimensional astronomical tide and storm surge coupling model was established to simulate three typical types of typhoons in the area. The Holland parameter model was used to simulate the wind field and wind pressure of the typhoon and the Japanese 55-year reanalysis data were added as the background wind field. The offshore boundary information was provided by an improved Northwest Pacific Ocean Tide Model. Typhoon-induced storm surges along the Jiangsu coast were calculated based on analysis of wind data from 1949 to 2013 and the spatial distribution of the maximum storm surge levels with different types of typhoons, providing references for the design of sea dikes and planning for control of coastal disasters.

Keywords: Jiangsu coast; Typhoon-induced storm surge; Numerical simulation; Holland parameter model; ADCIRC

1. Introduction

Storm surges induced by typhoons are among the most popular research topics in flood prevention and engineering design along coastal areas (Chen et al., 2009; Zhang et al., 2013). For example, according to the nuclear safety guide issued by the National Nuclear Safety Administration of China (1990), the probable maximum storm surge of the sea area around a nuclear power station is the essential element that determines the design basis of the flood. The design high tide level of nuclear power stations under construction or soon to be under construction is determined as the sum of the maximum astronomical tide level and the probable maximum storm surge level according to international standards (Liang and Zou, 2004).

In terms of modeling storm surges along the Jiangsu coast, probable maximum storm surge levels of Haizhou Bay along the Jiangsu coast have been calculated by a numerical model of the storm surge, governed by a depth-averaged flow equation in spherical coordinates, and verified by five cases of remarkable extratropical storm surges with a maximum storm surge level of 3.36 m (Yu et al., 2002; Wu et al., 2002). A high-resolution storm surge model along the Jiangsu coast has been built using the explicit difference method (Zhang, 2008), showing that the stability was low and the computation time was long. Several typhoons striking Jiangsu Province have been simulated using the weather research and forecasting (WRF) model and Delft 3D model in order to investigate the influence of storm surges on the radial sand ridges off the Jiangsu coast with the sea level rising (Yu et al., 2014). The hydrodynamics in the Jiangsu sea waters during Typhoon Damrey have been simulated and a good fit was generated between the simulated and measured values of the typhoon

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data (Wang et al., 2015), where the gradient wind field of Typhoon Damrey was computed by a Jele wind parameters model, and then combined with the ambient wind field from the United States National Centers for Environmental Prediction (NCEP).

In this study, hydrodynamic simulations were carried out to investigate the storm surge along the Jiangsu coast during different typhoons, based on the tracks and parameters of the hypothetical typhoons. The calculated surge levels show the spatial distribution of the maximum storm surge levels with different types of typhoons, providing valuable references for planning and control of coastal disasters.

2. Method

2.1. Model description

The water levels of tide gauges consist of the astronomical tide level and storm surge level during the typhoon period. This study built an astronomical tide and storm surge coupling model and validated the reasonability of the model topography, the boundary conditions, and the wind field. The surges caused by hypothetical typhoons along the Jiangsu coast were calculated using the storm surge model.

The numerical model included three sub-models, which were the wind field and wind pressure model, an improved Northwest Pacific Ocean Tide Model (a large model), and a two-dimensional (2D) typhoon storm surge model for the Jiangsu coast (a small model). The Holland parameter model was used to simulate the wind field and pressure field of the typhoon. The improved Northwest Pacific Ocean Tide Model (Zhang et al., 2012) provided the open boundary water levels for the 2D typhoon storm surge model, and the latter calculated the surge along the Jiangsu coast.

The improved Northwest Pacific Ocean Tide Model uses the 2D tidal propagation equation in spherical coordinates (Zhang et al., 2013), with a domain covering the East China Sea, South China Sea, Philippine Sea, Japan Sea, Sulu Sea, and nearby Pacific Ocean areas. The initial flow velocity is zero. When computing the coupled water level of the astronomical tide level and storm surge level, the open boundary condition for the large model was provided by a tidal prediction system (NOA. 99b), developed by the National Astronomical Observatory of Japan, with 16 short-period tidal constituents (M_2, S_2, K_1, O_1, N_2, P_1, K_2, Q_1, M_1, J_1, OO_1, $2N_2$, Mu_2, Nu_2, L_2, and T_2) and 7 long-period tidal constituents (M_{tm}, M_f, M_{Sf}, M_m, M_{Sm}, S_{sa}, and S_a) (Matsumoto et al., 2000), and the boundary conditions for the small model are the coupled water level of the astronomical tide level and storm surge level derived from the large model. While the storm surge is simulated alone, the open boundary water level for the large model is set as zero, so that the large model only provides the storm surge level for the small model. The model was validated with four main constituents (M_2, S_2, K_1, and O_1) of 435 tide gauges listed in the Admiralty Tide Table and the strong agreement indicated that the model is capable of simulating the tidal system of the Bohai Sea, the Huanghai Sea, and the East China Sea.

2.1.1. Wind field and wind pressure model

The wind field and wind pressure model adopted the Holland parameter model, which is the most popular method used to simulate typhoon storm surges. The Tropical Cyclone Best Track Dataset issued by the Shanghai Typhoon Institute of the China Meteorological Administration was used as the input conditions for the model to simulate typhoons (Ying et al., 2014).

The Holland parameter model relies on the primary assumption of a radially symmetric pressure field, but with a modified rectangular hyperbola to give the pressure p at any radius (r) from the typhoon center as follows:

$$p(r) = p_c + \Delta p \exp\left[-\left(\frac{R_{\max}}{r}\right)^B\right] \tag{1}$$

where $p(r)$ is the surface pressure at a distance r from the typhoon center; p_c is the central pressure; Δp is the difference between the ambient pressure (p_n) and the central pressure ($\Delta p = p_n - p_c$), and the value of the first anti-cyclonically curved isobar is p_n in practice; $R_{\max}$ is the radius to the maximum wind speed, referring to the distance from the typhoon center to the region of the maximum wind speed; and B is the so-called profile *peakedness* used to characterize the shape of the radial pressure profile.

Gradient winds in the upper atmosphere are derived from the balance between the centrifugal and Coriolis forces acting outwards and the pressure acting inwards:

$$\frac{V_g^2(r)}{r} + fV_g(r) = \frac{1}{\rho_a}\frac{dp(r)}{dr} \tag{2}$$

where $V_g(r)$ is the gradient wind speed (m/s) at a distance r from the typhoon center; f is the Coriolis parameter and $f = 2\omega\sin\varphi$; ω is the angular speed of the Earth's rotation, set to be 7.27×10^{-5} rad/s; φ is the latitude; and ρ_a is the air density (assumed to be constant at 1.15 kg/m^3 in the Holland parameter model).

Substituting the pressure field equation (Eq. (1)) into the force balance equation (Eq. (2)) will yield the gradient wind field $V_g(r)$:

$$V_g(r) = \left\{\frac{B}{\rho_a}\left(\frac{R_{\max}}{r}\right)^B \Delta p \exp\left[-\left(\frac{R_{\max}}{r}\right)^B\right] + \left(\frac{rf}{2}\right)^2\right\}^{\frac{1}{2}} - \frac{rf}{2} \tag{3}$$

In the region of the maximum wind speed, the Coriolis force is small compared to the pressure gradient and centrifugal forces, so the Coriolis force may be ignored and Eq. (3) can be simplified into

$$V_g(r) = \left\{\frac{B}{\rho_a}\left(\frac{R_{\max}}{r}\right)^B (p_n - p_c)\exp\left[-\left(\frac{R_{\max}}{r}\right)^B\right]\right\}^{\frac{1}{2}} \tag{4}$$

According to the distribution of typhoon wind speed, the maximum wind speed $V_{\max}$ occurs at $R_{\max}$. Then, replacing r in Eq. (4) with $R_{\max}$ will lead to