Ocean Engineering 163 (2018) 1–14

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Generating potential risk maps for typhoon-induced waves along the coast of Taiwan

Hung-Ju Shih[a], Hongey Chen[a,b], Ting-Yu Liang[a], Huei-Shuin Fu[a], Chih-Hsin Chang[a], Wei-Bo Chen[a,*], Wen-Ray Su[a], Lee-Yaw Lin[a]

[a] National Science and Technology Center for Disaster Reduction, New Taipei City, 23143, Taiwan
[b] Department of Geosciences, National Taiwan University, Taipei City, 10617, Taiwan

ARTICLE INFO

Keywords:
Potential risk maps
Typhoon-induced wave
Tide-surge-wave model
Taiwanese waters

ABSTRACT

Typhoon-induced waves threaten the coastal areas of Taiwan each year. The roaring waves caused by typhoon Meranti (2016) even destroyed a lighthouse in a fishing port on the southwestern coast of Taiwan. Therefore, there has been increased interest in creating potential risk maps for typhoon-induced waves along the coast of Taiwan. In this study, the highest intensity and lowest intensity typhoons (HITs and LITs, respectively) for each category from 1977 to 2016 were selected. A fully coupled tide-surge-wave model was utilized to map the distributions of maximum significant wave heights for 18 typhoon events. Each map was classified into one of 5 levels and employed to generate maximum and minimum potential risk maps for typhoon-induced waves. Our results demonstrate that the northern and the eastern coasts of Taiwan are threatened by violent waves (significant wave heights (SWHs) range from 7 to 11.5 m) over a coastline length of 236.4 km and roaring waves (SWHs exceeding 11.5 m) over a coastline length of 298.1 km under HIT conditions. The lengths of coastline threatened by big waves (SWHs ranging from 3 to 6 m) and small waves (SWHs less than 3 m) are 637.7 km and 553.4 km, respectively, under LIT conditions.

1. Introduction

Typhoons that make landfall in coastal areas are among the most serious natural disasters (Smith, 1996; Nicholls et al., 2007; Bertin et al., 2015). The direct threats of a typhoon can be devastating and include losses of human life and property damage primarily derived from destructive winds, heavy rainfall, storm surges and roaring waves, as well as debris flows caused by continuous heavy rainfall in mountainous areas (Lee and Kim, 2015). The catastrophes caused by large typhoon-induced waves generally include severe damage in coastal and offshore regions (Pang et al., 2013). Extreme waves from typhoons threaten human lives and infrastructure in Taiwan. For example, a lighthouse in a fishing port on the southwestern coast of Taiwan was destroyed during typhoon Meranti (2016). Ocean surface waves subject to extreme weather conditions, such as typhoons or hurricanes, are of great interest to oceanographers and ocean engineers (Young, 1999; Liu et al., 2017). Therefore, there has been increased interest in creating potential risk maps for typhoon-induced waves (PRMTWs) along the coast of Taiwan using numerical models.

Studies employing numerical simulations of typhoon- and wind storm-generated sea states have been continuously conducted for several decades (Cardone et al., 1996; Moon et al., 2003; Babanin et al., 2011; Liu et al., 2017). Third-generation spectral wind wave models are capable of predicting wave heights under severe meteorological conditions (i.e., typhoons) as long as the wind field over the sea surface is accurately provided (The WAMDI Group, 1988).

The effects of surface waves on tidal currents or tidal currents on surface waves, i.e., wave-current interactions, are among the most important mechanisms in coastal hydrodynamics. Wave propagation over spatially varying currents, especially typhoon-induced strong currents, can cause refraction (Kudryavtsev et al., 1999; Ris et al., 1999), and wave steepening can occur if the current is opposite the direction of waves (Romero et al., 2017). Enhanced wave breaking is expected because wave-current interactions modulate the bottom roughness (Phillips, 1984; Munk et al., 2000; Olabarrieta et al., 2014); moreover, extreme wave heights can result from wave-current interactions (White and Fornberg, 1998; Janssen and Herbers, 2009; Onorato et al., 2011; Toffoli et al., 2015).

It is also necessary to consider the interactions between tides and waves in numerical models to accurately simulate the coastal hydrodynamics and sea states in energetic waters, including in studies of marine energy (Hashemi and Neill, 2014), sediment transport, storm

* Corresponding author.
E-mail addresses: wbchen@livemail.tw, wbchen@ncdr.nat.gov.tw (W.-B. Chen).

https://doi.org/10.1016/j.oceaneng.2018.05.045
Received 19 December 2017; Received in revised form 12 March 2018; Accepted 27 May 2018

surges and extreme wind waves (Hashemi et al., 2015). Increases in the incident wave height are evident during rising tides (Davidson et al., 2008). Coastal wave heights are mainly controlled by the total water depth; therefore, the effects of tides and surges on waves must also be considered because waves contribute to the total water level by means of wave setup through radiation stress. Additionally, wind waves and elevated water levels can enhance flooding in low-lying coastal areas because the total water level is a combination of mean sea level, tides and storm tidal (meteorological surge plus wind-induced surge) waves, which are often generated by the same storm event (Wolf, 2009).

In the present study, the effects of tide-wave and wave-current interactions on wave hindcasts are considered using an unstructured grid, fully coupled tide-surge-wave model. The model consists of a coastal hydrodynamic model and a third-generation spectral wave model. The same computational domain and unstructured grid system are shared in the coupled model. The advantage of this scenario is that errors arising from data interpolation between the two models can be avoided. Additionally, the modeling system can efficiently perform parallel computations.

The primary objectives of this study are as follows: (1) implement the tide-surge-wave fully coupled high-resolution model in a study of Taiwanese waters; (2) validate the fully coupled model with available measured data; (3) reproduce spatial distribution maps of the maximum significant wave heights (SWHs) for selected typhoons; (4) create maximum and minimum PRMTWs; and (5) assess the length of the coastline under threat from each SWH level.

2. Methodology and data

2.1. Coastal hydrodynamic model

The hydrodynamics of the waters surrounding Taiwan were simulated with the novel community model SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model). SCHISM is a derivative product built from the original SELFE model (Semi-implicit Eulerian-Lagrangian Finite-Element/volume; Zhang and Baptista, 2008) and distributed with an open-source Apache v2 license. The model includes many enhancements and upgrades, such as a new extension to a large-scale eddy regime and a seamless cross-scale capability ranging from the creek to ocean scales (Zhang et al., 2016). SCHISM and SELFE have been widely used to simulate tsunami propagation (Zhang et al., 2011), predict water quality and ecosystem dynamics (Rodrigues et al., 2009, 2011; Chen and Liu, 2017), analyze oil spill diffusion and transport (Azevedo et al., 2009), generate inundation maps (Fortunato et al., 2013; Chen and Liu, 2016), evaluate inundation extents induced by extreme river flows, typhoons or hurricanes (Chen and Liu, 2014; Wang et al., 2014) and estimate tidal current power (Chen et al., 2017a). The surface circulation feature is similar to that at the bottom during spring (Wu et al., 2007), and weak winter stratification is caused by vertical mixing in Taiwanese waters (Oey et al., 2010); hence, the SCHISM model employed in this study is a two-dimensional, vertically integrated model with a barotropic mode. The governing equations in the Cartesian coordinate system and two-dimensional form are given as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial uH}{\partial x} + \frac{\partial vH}{\partial y} = 0, \tag{1}$$

$$\frac{Du}{Dt} = fv - \frac{\partial}{\partial x}\left\{g(\eta - \alpha\hat{\psi}) + \frac{P_A}{\rho_0}\right\} + \frac{\tau_{sx} + \tau_{rx} - \tau_{bx}}{\rho_0 H}, \text{ and,} \tag{2}$$

$$\frac{Dv}{Dt} = -fu - \frac{\partial}{\partial y}\left\{g(\eta - \alpha\hat{\psi}) + \frac{P_A}{\rho_0}\right\} + \frac{\tau_{sy} + \tau_{ry} - \tau_{by}}{\rho_0 H}, \tag{3}$$

where $\eta(x, y, t)$ is the free surface elevation; $H = \eta + h$ is the total water depth; h is the bathymetric depth; $u(x, y, t)$ and $v(x, y, t)$ are the horizontal velocity components in the x- and y-directions, respectively; f is the Coriolis factor; g is the acceleration due to gravity; $\hat{\psi}$ is the Earth's tidal potential; α is the effective Earth elasticity factor; ρ_0 is the reference density of water; and $P_A(x, y, t)$ is the atmospheric pressure at the free surface. τ_{sx} and τ_{sy} are the wind stress components in the x- and y-directions, respectively, and can be expressed as follows:

$$\tau_{sx} = \rho_a C_s \sqrt{W_x^2 + W_y^2}\, W_x, \quad \text{and} \tag{4a}$$

$$\tau_{sy} = \rho_a C_s \sqrt{W_x^2 + W_y^2}\, W_y, \tag{4b}$$

where C_s is the wind drag coefficient; ρ_a is the air density; and w_x and w_y are the 10-m wind speed components above the sea surface in the x- and y-directions, respectively. C_s is often regarded as an increasing function of wind velocity, but Powell et al. (2003) suggested that C_s should be limited at high wind speeds. The formula for calculating C_s in SCHISM is as follows:

$$C_s = 1.0^{-3}\begin{cases} (0.61 + 0.063 \times 6.0), & W < 6.0 \\ (0.61 + 0.063W), & 6.0 \le W \le 50.0, \\ (0.61 + 0.063 \times 50.0), & W > 50.0 \end{cases} \tag{5}$$

where W is the resultant wind speed 10 m above the sea surface.

τ_{bx} and τ_{by} are the bottom shear stress components in the x- and y-directions, respectively, and can be computed by the following formulas:

$$\tau_{bx} = \rho_0 C_d \sqrt{u^2 + v^2}\, u, \quad \text{and} \tag{6a}$$

$$\tau_{by} = \rho_0 C_d \sqrt{u^2 + v^2}\, v, \tag{6b}$$

where C_d is the bottom drag coefficient. Specifically, C_d can be parameterized as follows:

$$C_d = gn^2/H^{1/3}, \tag{7}$$

where n is the Manning coefficient, which was set to 0.025 in the model based on the type of the sea-bottom material. However, the bottom drag coefficient C_d varies with H according to Equation (9).

τ_{rx} and τ_{ry} are the wave-induced stress (i.e., radiation stress) components in the x- and y-directions, respectively, and can be computed following the methods of Longuet-Higgins and Stewart (1962, 1964):

$$\tau_{rx} = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}, \quad \text{and} \tag{8a}$$

$$\tau_{ry} = -\frac{\partial S_{xy}}{\partial x} - \frac{\partial S_{yy}}{\partial y}, \tag{8b}$$

where S_{xx}, S_{xy} and S_{yy} are the wave radiation stress components. According to Battjes (1974), these components can be represented as follows:

$$S_{xx} = \int_0^{2\pi}\int_0^{\infty} N\sigma \frac{C_g}{C_p}\sin(\theta)\, d\theta d\sigma, \tag{9a}$$

$$S_{xy} = S_{yx} = \int_0^{2\pi}\int_0^{\infty} N\sigma \left[\frac{C_g}{C_p}(\cos^2(\theta) + 1) - \frac{1}{2}\right] d\theta d\sigma, \text{ and} \tag{9b}$$

$$S_{yy} = \int_0^{2\pi}\int_0^{\infty} N\sigma \left[\frac{C_g}{C_p}(\sin^2(\theta) + 1) - \frac{1}{2}\right] d\theta d\sigma, \tag{9c}$$

where N is the wave action, σ is the relative angular frequency of waves, θ is the wave direction, and C_g and C_p are the wave group velocity and wave phase velocity, respectively.

2.2. Third-generation spectral wave model

Phase-averaged spectral wind wave models have the advantage of efficiently hindcasting sea states in realistic applications (Komen et al.,