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Numerical analysis of impacts of 2011 Japan Tohoku tsunami on China Coast*

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Abstract: On the 11th of March, 2011, a subduction earthquake of magnitude Mw9.0 happened at the northeast of Japan, generating a tsunami which resulted in huge damage in Japan. Okada's elastic fault model is used to generate the deformation of the sea bottom based on USGS sources and UCSB sources respectively. The shallow water equations are solved by the adaptively refined finite volume methods so that it can compute the propagation of tsunami in the Pacific Ocean efficiently. The computed time series of the surface elevation are compared with the measured data from NOAA real-time tsunami monitoring systems for model validation, and UCSB sources derive better results than USGS sources. Furthermore, one nested domain with fine grid and higher topography resolution is combined to compute numerically this tsunami spreading in the Bohai Sea, Yellow Sea, East China Sea, and North of South China Sea. The impacts on China Coast and seas are analyzed and discussed. The results show that the tsunami has almost no impact in the Bohai Sea and Yellow Sea. It has some kind impact on the East China Sea and South China Sea. However, maximum wave height on China Coast is smaller than 0.5 m. It is thus concluded that the 2011 Tohoku tsunami did not generate a significant influence on China Coast.

key words: Tohoku tsunami, numerical simulation, shallow water equation, China Coast

Introduction

On the 11th of March, 2011, an earthquake of magnitude $Mw = 0.9$ happened at the northeast of Japan, generating a tsunami which resulted in huge damage in Japan. For the reason of the high quality of earthquake preparedness in Japan, the earthquake itself caused little damage. However, the subsequent tsunami resulted in the mortality of more than 15 000 people and extensive damaged coastal settlements and infrastructures[1]. Besides, the radiation leak of Fukushima Nuclear Power Plant caused by the tsunami triggered tremendous environment damage which is difficult to estimate[1]. The tsunami also struck the most of the coast of the Pacific rim countries and regions. Therefore, it is vital to simulate the tsunami and predict the impact on China Coast.

Recently, several scholars have simulated this tsunami and analyzed its impacts. Popinet[2] took the Gerris model to simulate the inundation area. This model is based on the shallow water equations. The

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numerical algorithm has some additional capabilities of quadtree-based adaptive discretisation, orthogonal coordinates and parallelism. Zhang et al.[3] used a tsunami model named GeoClaw to simulate the 2011 Tohoku tsunami in the near field and the inundation to the Sendai Airport and Fukushima nuclear power plant with high performance computers with many-core architectures. Grilli et al.[4] developed a new tsunami source by using 3-D finite element model and simulated the tsunami with a Boussinesq model. Saito et al.[5] estimated the initial tsunami water height distribution by the inversion analysis based on the dispersive tsunami simulations. Watanabe et al.[6] calculated the maximum wave heights along Japan Coasts with the shallow water equations.

This article adopts a tsunami model named GeoClaw[7] which was developed by the University of Washington to simulate the 2011 Tohoku tsunami. The model is based on the nonlinear shallow water equations, taking into account the nonlinear effect of the tsunami wave propagation in coastal oceans, whereas it does not involve the dispersion effect. It is based on the tsunami wave height tracking to determine whether to refine mesh. In view of the huge tsunami destruction, rapid tsunami hazard and risk assessments are necessary. Therefore, this tsunami model which ensure the calculation accuracy and calculation efficiency can meet this demand. A numerical investigation of the 2011 Tohoku tsunami based on two earthquake sources (USGS and UCSB) and the assessments of impacts on China coasts are presented, which includes tsunami propagation in the Pacific Ocean for the model validation and tsunami wave height distribution along the coasts of China.

1. Model introduction

1.1 *Governing equations*

The depth-averaged nonlinear shallow water equations are used to formulate the propagation of tsunamis. In the Cartesian coordinates, the mass conservation equation and the momentum conservation equations can be written as:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(hu)+\frac{\partial}{\partial y}(hv)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(hu)+\frac{\partial}{\partial x}\left(hu^2+\frac{1}{2}gh^2\right)+\frac{\partial}{\partial y}(huv)=-gh\frac{\partial b}{\partial x}-\tau_x \tag{2}$$

$$\frac{\partial}{\partial t}(hv)+\frac{\partial}{\partial x}(huv)+\frac{\partial}{\partial y}\left(hv^2+\frac{1}{2}gh^2\right)=-gh\frac{\partial b}{\partial y}-\tau_y \tag{3}$$

in which t is time, $h(x,y,t)$ is total water depth, $b(x,y)$ is the bottom elevation function describing natural bathymetry, $u(x,y,t)$ and $v(x,y,t)$ are the two components of the depth-averaged velocities in the x and y directions. The gravity acceleration is denoted by g. The components of the non-linear bottom friction term are

$$\tau_x=\frac{gn^2}{h^{7/3}}hu\sqrt{(hu)^2+(hv)^2}\ ,$$

$$\tau_y=\frac{gn^2}{h^{7/3}}hv\sqrt{(hu)^2+(hv)^2} \tag{4}$$

where n is the Manning coefficient, representing the roughness of the bottom.

Table 1 Parameters of the tsunami fault zone

Length (km)	Width (km)	Dislocation	Dip (°)	Slip (°)	Strike (°)	Depth (km)
400	200	16.3	14	81	193	24

The shallow water equations can be formulated as the more general form of hyperbolic systems

$$\boldsymbol{q}_t+\boldsymbol{f}(\boldsymbol{q})_x+\boldsymbol{g}(\boldsymbol{q})_y=s \tag{5}$$

where $\boldsymbol{q}$ is the vector of unknowns, $\boldsymbol{f}(\boldsymbol{q})$ and $\boldsymbol{g}(\boldsymbol{q})$ is the vector of corresponding fluxes, and $\boldsymbol{s}$ is a vector of source terms:

$$\boldsymbol{q}=\begin{bmatrix}h\\hu\\hv\end{bmatrix},\quad \boldsymbol{f}(\boldsymbol{q})=\begin{bmatrix}hu\\hu^2+\frac{1}{2}gh^2\\huv\end{bmatrix},$$

$$\boldsymbol{g}(\boldsymbol{q})=\begin{bmatrix}hv\\huv\\hv^2+\frac{1}{2}gh^2\end{bmatrix},\quad \boldsymbol{s}=\begin{bmatrix}0\\-gh\frac{\partial b}{\partial x}-\tau_x\\-gh\frac{\partial b}{\partial x}-\tau_y\end{bmatrix} \tag{6}$$

1.2 *Numerical aspects*

The finite volume method is adopted to discretize Eq.(5) together with the first-order Godunov method

$$Q_i^{n+1}=Q_i^n-\frac{\Delta t}{\Delta x}(F_{i+1/2}^n-F_{i-1/2}^n)-\frac{\Delta t}{\Delta y}(G_{i+1/2}^n-G_{i-1/2}^n)+\Delta t S_{i,j}^n \tag{7}$$