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Preliminary numerical simulation of potential earthquake-induced tsunami in East China Sea[*]

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Abstract

In this paper, we present a numerical simulation of the propagation of a tsunami in the East China Sea, which might be induced by a hypothetical M8.5 earthquake in Okinawa Trough. Our results show that the initial maximum wave height of tsunami could reach as high as 4.3 m for the hypothetical earthquake. It would take 3.5~4 hours for the tsunami to propagate to the coast of Zhejiang Province, and 7~8 hours to the near-shore of Shanghai. The peak tsunami height could be up to about 2 m in the coast of Zhejiang Province. Based on the numerical experiments, we plot the arrival time contours of tsunami in East China Sea and time history curves on the three observational stations, and discussed the significance of the pre-analysis.

Key words: **potential tsunami**; **numerical simulation**; **maximum tsunami height**; **arrival time contours**
CLC number: P315.3^{+}3 **Document code**: A

Introduction

Tsunami is one of the most severe natural disasters faced by coastal regions around the world. While a number of geological events such as volcano eruption and landslide in oceans could generate tsunamis, the most common source inducing a tsunami is the submarine earthquake. At present, earthquake predictions are still unreliable. The damage could be devastating if an earthquake-induced tsunami really occurs and a coastal area is not prepared and no early warning is issued. However, it's possible to mitigate the disaster by sending out an early warning based on the earthquake magnitude and the predicted impact of the tsunami, especially for those areas far away from the epicenter, where people would have enough time to evacuate.

The tsunami arrival time and its wave height are two important parameters for tsunami early warning. For most of existing models of tsunami simulation, if the detailed fault information is known, both arrival time and wave height can be predicted fairly accurately. Therefore, real time numerical simulation is critical for tsunami early warning. When a submarine earthquake occurs,

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Foundation item: National Natural Science Foundation of China (40576022) and the Joint Seismological Science Foundation of China (106078).

[♣] **Author for correspondence**: wunyanling05@mails.gucas.ac.cn the fault parameters, once available, are sent immediately into a numerical model to start a simulation. The predicted arrival time and the wave heights could soon be released to the affected regions based on the simulation results. Unfortunately, in practice, shortly after occurrence of an earthquake, the detailed information is often not available for a simulation to start. Moreover, numerical simulations and data processing also take considerable time before getting a forecasting ready. Considering the high travel speed of tsunamis, it’s difficult to release tsunami warning by real time numerical simulation for near-field regions.

Although several factors may limit the use of real time numerical simulation for a tsunami early warning, it seems more feasible to do numerical simulations before an earthquake. Based on the historical seismicity and tectonic settings, hazardous tsunami sources can be outlined and pre-studies can be performed to identify possible affected regions. Once an earthquake occurs, an early warning can be quickly released from these pre-studies. Countries around the South China Sea and Taiwan areas have been carrying out pre-studies of potential earthquake-inducing tsunami hazards (Liu *et al*, 2007).

The Okinawa Trough is considered as one of the most possible tsunami-generating source regions, which may impact eastern Chinese mainland. This paper pre-studied the arrival time and possible tsunami wave heights in eastern coastland of China when an earthquake-inducing tsunami is presumed to occur in the Okinawa Trough. Accordingly, once a tsunami is generated in this region in the future, the arrival time and tsunami wave heights may be quickly estimated from these preliminary analyses.

1 Tectonic settings and seismicity

The East China Sea is a continental marginal sea surrounded by the Chinese mainland, Taiwan, Korea, Kyushu and Ryukyu. This region can be divided into the continental shelf, Okinawa Trough, Ryukyu Arc and Ryukyu Trench from west to east. The continental shelf of East China Sea is about several hundreds kilometers wide and less than 100 m deep. The Okinawa Trough strikes NE-SW with 840 km long, 36~120 km wide. The bathymetry is 500~1 000 m in the northern Okinawa Trough, 700~1 500 m in the middle Okinawa Trough, and 1 000~2 000 m in the southern Okinawa Trough, with the deepest part being 2 719 m (Figure 1).

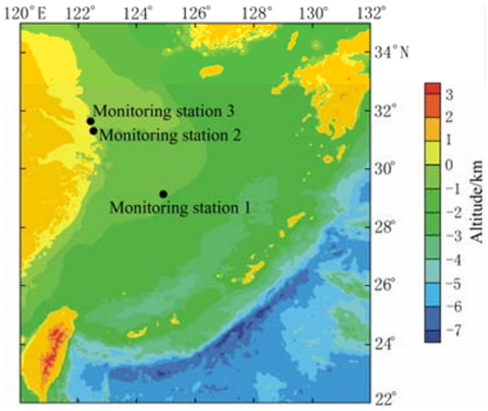

Figure 1 Bathymetry of East China Sea

The Okinawa Trough is a back-arc basin of the Ryukyu Trench Arc Back-Arc system, and it shows the characteristic of a tensile-split-sink. There are two types of rupture, one is the parallel rupture, including a lot of high-angle normal faults that is the same to the strike of the Okinawa Trough; another type is the transverse rupture, including Tokara fault and Miyako fault showing the characteristic of horizontal slip. The tectonic motions and volcano eruptions have occurred frequently in the Okinawa Trough. The fringe area of East China Sea is the Ryukyu-Taiwan earthquake belt, which is a part of circum Pacific earthquake belt and very active. In the 20th century, earthquakes with $M\geq 7.0$ have occurred more than

40 times in the Ryukyu-Taiwan earthquake belt, which include the *M*8.2 Amami-Oshima offshore earthquake in 1911, the *M*8.1 Hua-lian offshore earthquake in 1920 and the *M*7.7 northwestern Miyako-jima offshore earthquake in 1938 (Liu *et al*, 2006; Wu and Yu, 2006). On April 24, 1771, a *M*7.4 submarine earthquake near Ishigaki-Jima generated a huge tsunami. The wave heights recorded in Ishigaki Island and Miyako Island exceeded 10 m, causing significant damage including approximately 12 000 casualties (Nakamura, 2006). The Chinese ancient books also recorded some tsunamis striking the coastal area of eastern China (Wang *et al*, 2005). Considering the tectonic background, the characteristic of bathymetry and the historical seismicity in Okinawa Trough, future big earthquake are likely to occur again in this region, which potentially generates a damaging tsunami.

2 Tsunami propagation model

The potential tsunami in Okinawa Trough is local tsunami, so the model describing its propagation in East China Sea should include the term of ocean bottom friction in the non-linear shallow wave model (Yu *et al*, 2001; Choi, 2005). In Cartesian coordinate, it can be expressed as:

$$\begin{gathered}\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\tau_x D=0\\ \frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\tau_y D=0\\ \frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0\end{gathered}\tag{1}$$

Where η is free surface elevation; $D=h+\eta$ is the total water depth; *M* and *N* are the volume fluxes in *x*, *y* directions, respectively:

$$\begin{gathered}M=\int_{-h}^{\eta} u\mathrm{d}z=\bar{u}D\\ N=\int_{-h}^{\eta} v\mathrm{d}z=\bar{v}D\end{gathered}\tag{2}$$

$\bar{u}, \bar{v}$ represent the depth-averaged velocities in *x*, *y* directions, respectively. τ_x, τ_y are ocean bottom friction in *x*, *y* directions, Manning gave a formula as follows:

$$\begin{gathered}\tau_x=\frac{gn^2}{D^{10/3}}M\sqrt{M^2+N^2}\\ \tau_y=\frac{gn^2}{D^{10/3}}N\sqrt{M^2+N^2}\end{gathered}\tag{3}$$

Where *n* is Manning frictional coefficient having a value between 0.01 and 0.06. n=0.010 is metallic smooth seafloor, and n=0.025 represents a seafloor in good condition, n=0.060 means the seafloor is in bad condition. Here we choose n=0.025 for the seafloor condition of East China Sea.

3 Hypothetic fault plane and numerical simulating

An earthquake tsunami is generated by seafloor fault dislocation, which can be determined from fault parameters and the earthquake magnitude. The seafloor displacement is computed based on the elastic dislocation theory. Using the formula $M_W=2\log_{10}M_0/3-10.7$, we can compute the seismic moment M_0 for a given earthquake magnitude M_W. After knowing the moment M_0, fault area S and shear module μ, we then calculated the fault dislocation D by using the formula $M_0=\mu DS$. Finally we utilized the finite fault plane theory to calculate the seafloor displacement generated by the fault dislocation (Mansinha and Smylie, 1971). To determine seafloor displacement, more parameters are needed: focal depth d, dip angle δ and slip angle λ (Figure 2).

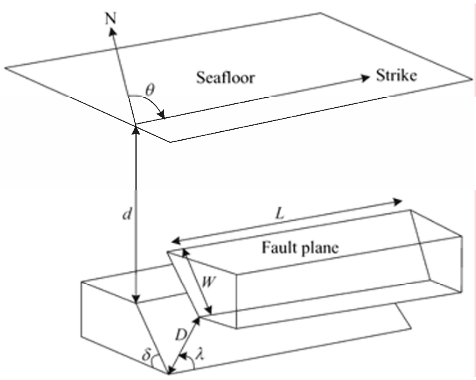

Figure 2 Fault model

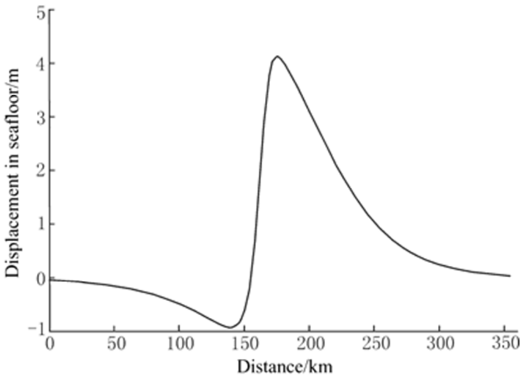

Figure 3 Transect profile of seafloor displacement

Based on historical earthquakes, we estimate that the maximum potential earthquake magnitude in East China Sea might reach 8.5. The most likely fault on which the event might occur is in the southern Okinawa Trough, assumed at 124.5°E, 25.2°N. The fault is 200 km long, 79 km wide and 10 km depth. The dislocation amounts to 15 m, and other parameters of the fault (strike, dip, slip) are 23°, 60°, 30°, respectively. The calculated seafloor displacement for this fault is shown in Figure 3. The maximum uplift of seafloor displacement is 4.3 m and the maximum depression is −0.9 m. An earthquake usually occurs with duration of a few seconds. With such a short duration, there is no time for the water above the fault zone to escape. In addition, the duration of fault motion is usually one to two orders less than the period of the tsunami wave. Thus, it is appropriate to assume that the seafloor deforms impulsively and the sea surface has the same deformation as the seafloor (Todorovska and Trifunac, 2001).

The propagation of a tsunami in East China Sea is simulated by a numerical program called COMCOT, which is short for Cornell Multi-grid Coupled Tsunami Model. COMCOT has been used to investigate many historical tsunami events, such as the 1960 Chilean tsunami and the 1992 Flores Islands (Indonesia) tsunami (Wang and Liu, 2006). COMCOT adopts a modified leap-frog finite difference scheme to solve (both linear and nonlinear) shallow water equations. In this paper, the simulated domain ranges from 120°E to 132°E in longitude and 22°N to 35°N in latitude with a grid size of 2 min and time step of 1 s. The bathymetry data is based on Etopo2 database. The dimension of grids is 361 by 391. A reflective boundary (vertical wall) was assigned as the “shoreline” (where water depth is less than 5 m) and the radiation open boundary was used for boundaries falling into the water region.

4 Results and analysis

We simulated an 8-h physical duration for the tsunami propagation in East China Sea and the results are plotted by the Tecplot software. The snapshots of the numerical tsunami propagation

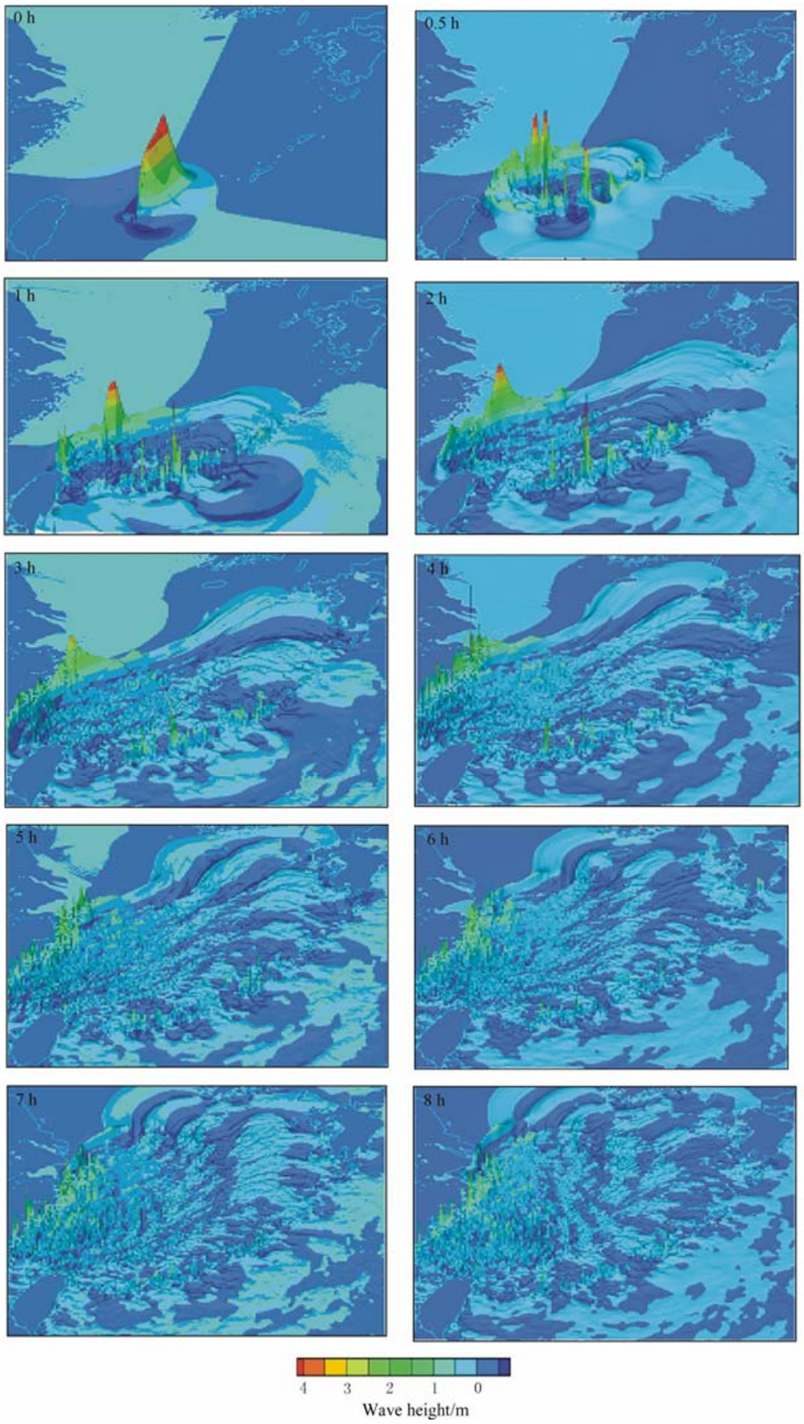

Figure 4 Snapshots of tsunami propagation for 0 to 8 hours

are shown in Figure 4.

It is shown from the above tsunami propagation that it takes half an hour for the tsunami to strike the northeast of Taiwan Island, about 4 hours to attack the coast of Zhejiang Province, and about 8 hours to arrive at the southeastern near-shore of Shanghai Municipality. We have set three observational stations in East China Sea (locations are shown in Figure 1). The time history plots of this numerical tsunami recorded by the 3 stations are shown in Figure 5. The curves reveal that the period of the tsunami is about 2 hours.

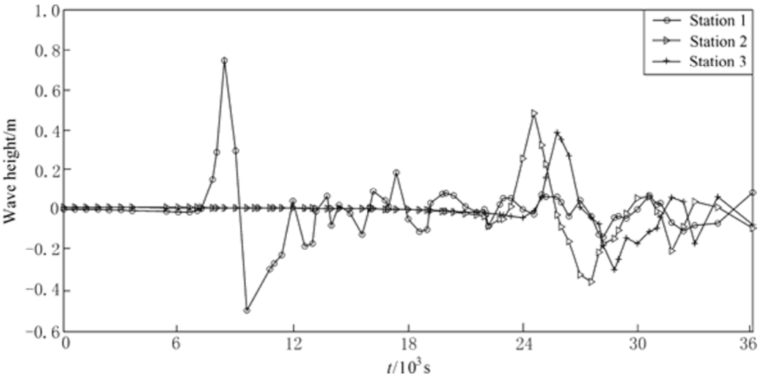

Figure 5 Time history plots at three stations

We also simulated the propagation of tsunamis generated by the two hypothetical earthquakes in the middle and north of Okinawa Trough respectively. Figure 6 shows the detailed arrival time contours of all three tsunamis. Based on numerical propagation simulations in East China Sea, we concluded that, once there is tsunami generated by *M*8.5 earthquake in Okinawa Trough, it takes at least 7 hours to arrive at the shoreline of Shanghai Municipality, with the wave height about 1 m; at least 3.5 hours to arrive at Zhejiang Province, with the wave heights exceed 1 m, even up to 2.4 m somewhere due to the bay effect and run-up in numerous offshore islands. The tsunami propagation in the Yangtze River and Hangzhou Bay is not computed because of the lower spatial resolution. The above wave height data is calculated from the tsunami generated by the maximum potential earthquake in East China Sea, so it is unlikely to become a reality. According to the computed probability of potential earthquake tsunami in littoral area of Chinese mainland, the probability of Shanghai Municipality subject to 2 m tsunami height is 0.52%, 1~2 m being 7.2%, and 0.5~1 m is 13.15% in this century (Liu *et al*, 2007).

5 Discussion and conclusions

This paper simulated the tsunami propagation in Okinawa Trough induced by a hypothetical potential *M*8.5 submarine earthquake. The preliminary numerical simulation indicate that the maximum height of initial tsunami incited by the *M*8.5 earthquake is 4.3 m, the tsunami strikes Zhejiang Province about 3.5~4 hours after the earthquake, and arrives at the near-shore of Shanghai Municipality after 7~8 hours. The wave heights are 1~2 m in the coast of Zhejiang Province and about 1 m in the shoreline of Shanghai Municipality. The wave height might be underestimated because of inaccurate bathymetry data in near-shore areas. On the other hand, the impact of the tsunami could also be overestimated since the magnitude of the potential earthquake is maximal in the region. As a result, it only has small chance to become a reality. However, once such a tsunami is generated in the East China Sea, this pre-study can help to rapidly estimate the impact regions, so that the government can take countermeasures timely.

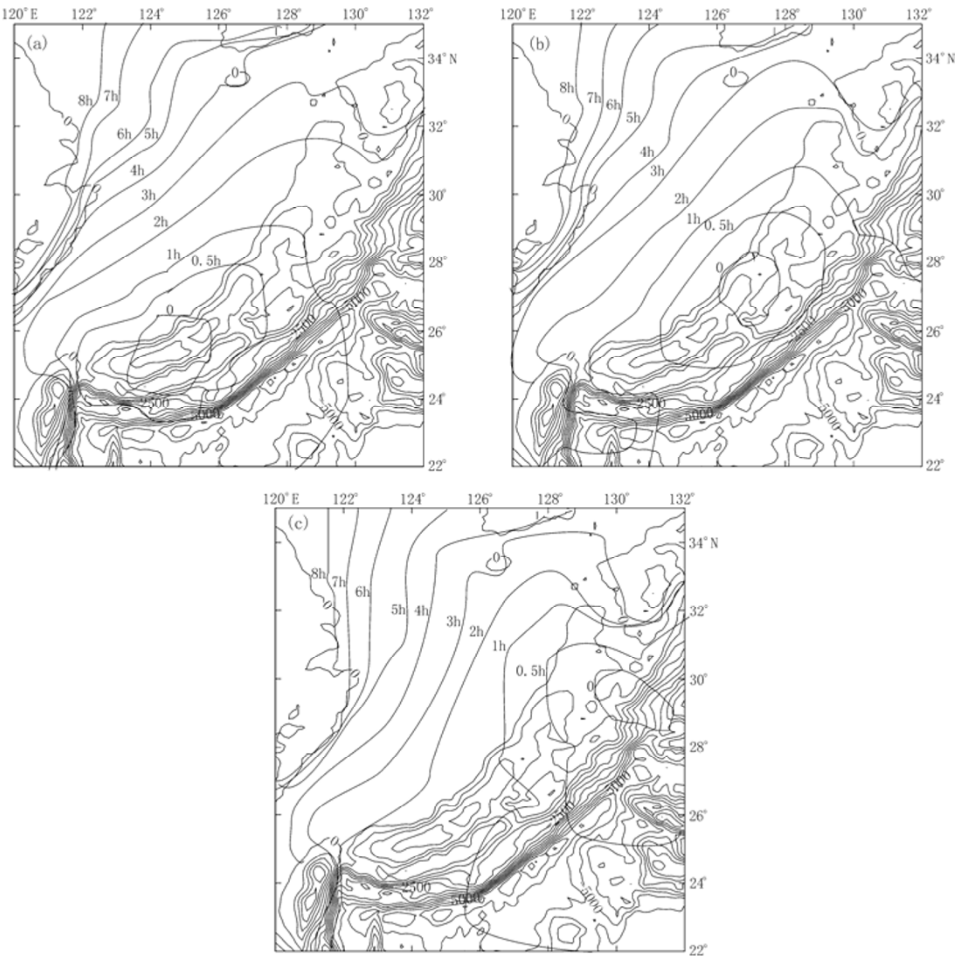

Figure 6 Arrival time contours of tsunami in southern Okinawa Trough (a), middle Okinawa Trough (b), northern Okinawa Trough (c)

In the simulation, the tsunami heights were derived with a grid size of 3.4 km. Because the actual near-shore topography has much smaller scales, the complex local bathymetry would influence the tsunami height severely. In the future, the simulation of tsunami propagation and inundation should be conducted in near-shore area with smaller grid size and more accurate bathymetry, so that we can improve the estimation of the Chinese tsunami hazards significantly.

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