Journal of Asian Earth Sciences 36 (2009) 2–12

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

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

Tsunami hazard and early warning system in South China Sea

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ARTICLE INFO

Article history:
Received 23 June 2008
Received in revised form 15 December 2008
Accepted 26 December 2008

Keywords:
Tsunami
Early warning system
Subduction zone
Inverse problem
Numerical simulation
South China Sea

ABSTRACT

In this paper, we discuss the potential tsunami hazard in the South China Sea region. We focus our discussions on the characteristics of tsunamis generated from earthquakes along the Manila subduction zone. A procedure is presented for establishing a tsunami early warning system in the region. A scenario case is used to demonstrate the feasibility of the early warning system.

1. Introduction

Tsunami is one of the most devastating natural coastal disasters. Most of large tsunamis are generated by submarine earthquakes occurring in subduction zones. Tsunamis can also be triggered by volcano eruptions and large landslides. Although the skill for predicting earthquake is still in its infancy, a tsunami warning system is still possible for a distant tsunami if the tsunami can be detected in the open-ocean. Information on the arrival time and the height of leading tsunami wave in areas far away from the source region can be predicted with some confidence (e.g., Wei et al., 2003).

Such a tsunami warning system is now operational in the Pacific Ocean and has proven its effectiveness and validity for several recent tsunami events. If a similar early warning system had been available in the Indian Ocean, the 2004 Indian Ocean tsunami would have caused much less damage in property and loss in human lives in Sri Lanka, India, Maldives and other coastal regions.

In the South China Sea (SCS) region, the Manila subduction zone has been identified as a high hazardous tsunamigenic earthquake source region. No earthquake larger than $M_w = 7.6$ has been recorded in the past 100 years in this region, suggesting a high probability for larger earthquakes in the future. And most alarmingly, there is no operational tsunami warning system in place in this region. If a tsunamigenic earthquake were to occur in this region in the near future, a tragedy with the magnitude similar to the 2004 Indian Ocean tsunami could repeat itself.

In this paper, potential tsunami hazard in SCS region is studied and a procedure for establishing a tsunami early warning system is presented (Satake, 1987; Titov et al., 2001). This system will be capable of releasing early warning information, including both tsunami arrival times and wave heights, to the surrounding countries for earthquakes along the Manila subduction zone. Using this information as input, inundation forecasts will also be possible by applying tsunami runup models in coastal regions of interest.

2. Hazardous tsunamigenic zones in South China Sea

In the 2006 USGS tsunami source workshop (Kirby et al., 2006), three subduction zones, the Manila subduction zone, Ryukyu subduction zone and N. Sulawesi subduction zone, were identified as having high potentials to generate hazardous tsunamis (Fig. 1).

Preliminary numerical studies have indicated that tsunamis generated from the Ryukyu subduction zone and N. Sulawesi subduction zone will not directly affect countries surrounding the South China Sea. Tsunamis generated from the Ryukyu subduction zone mostly propagate into the Pacific Ocean due to the strike angle of the potential thrust faults in this region. On the other hand, tsunamis generated from the N. Sulawesi subduction zone are most likely trapped inside the Celebes Sea. Neither of these subduction zones will have significant impacts on the surrounding countries of the South China Sea. Therefore, in this paper only the tsunamis generated from the Manila subduction zone will be investigated.

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doi:10.1016/j.jseaes.2008.12.010

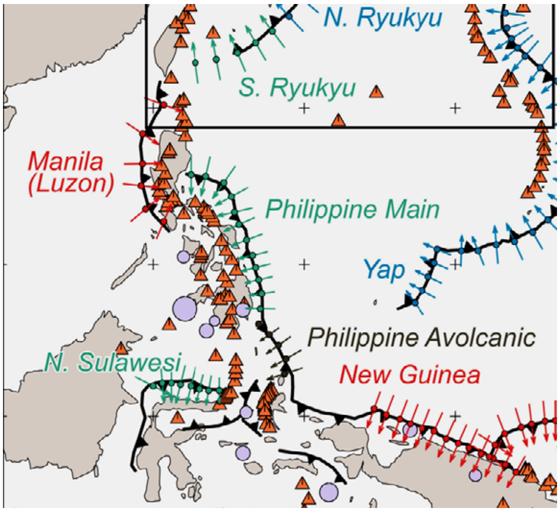

Fig. 1. Subduction zones near/in South China Sea (source: Kirby et al., 2006 USGS workshop).

2.1. Source region parameters along Manila Trench

The Manila subduction zone, or so-called Manila Trench, is where the Eurasian Plate subducts under the Philippine Sea Plate at a speed of 70 mm/year (Lin, 2000). Manila Trench, starting from the northern tip of Palawan, Philippine, evolves to the north along the Western edge of Luzon, Philippine and ends in Taiwan, with a total length about 1000 km. Earthquake records show that the largest earthquake in this subduction zone in the past 100 years is about $M_w = 7.5$ (the 1999 Chi–Chi earthquake was 7.6 and the 1934 earthquake offshore from the northern Luzon was 7.5), making this region the most tsunami-hazardous in the future (Lee, personal communication).

Along Manila Trench, six fault segments have been identified in USGS tsunami sources workshop 2006 (Kirby et al., 2006) as shown by the red crosses in Fig. 2.[1] The epicenters are slightly different from those recommended by Kirby et al. (2006) which are shown by yellow crosses in Fig. 2 (right panel). The same dip angles, as indicated by Kirby et al., are adopted for each fault plane. The rake angle is assumed 90° for all the fault planes, which will make a maximum contribution to the seafloor deformation. The focal depth, defined as the distance from the seafloor to top edge of a fault plane, is assumed to be 15 km, which is commonly observed in several major earthquake events in this region in the past. The fault parameters for each fault segment are summarized in Table 1.

The task for determining the width of a fault plane is non-trivial. The true fault plane width can only be estimated after an earthquake. Thus, the width can only be inferred from past earthquakes and/or from other empirical studies. Using the database of National Earthquake Information Center (NEIC), several historical events are used to estimate the width of fault plane.

On December 11, 1999 an $M_w = 7.3$ earthquake occurred. Its epicenter is marked by a yellow cross in Fig. 3. Seven small aftershocks are indicated by white dots. By drawing a rectangular region enclosing the main shock and aftershocks, the size of the source area for this event is outlined and the width of the fault plane for this event is estimated as 34 km (width of fault plane = measured width in Fig. 3 divided by cos(dip angle) = 30 km/cos(28°)).

Alternatively, the size of the ruptured area during an earthquake event may also be determined from empirical formulae. Wells and Coppersmith (1994) studied 421 historical earthquake events and 244 of these earthquakes with relatively reliable fault parameters were statistically analyzed. Empirical relationships among moment magnitude (M_w), rupture length, rupture width and dislocation were established. The calculated width of each fault plane with Wells and Coppersmith's relationships is given in Table 2. In this table, "SRL" denotes surface rupture length and "RLD" subsurface rupture length. It is clear that the width of each fault plane segment varies slightly. However, for simplicity, we choose a single width value, 35 km, for all fault plane segments in the present study. The fault parameters for these hypothetical fault planes are summarized in Table 3.

If we assume an earthquake with magnitude $M_w = 8.0$, with the fault parameters listed in Table 3, the amount of slip motions can be computed using the following equations:

$$M_o = \mu DLW \quad (1)$$

$$M_w = \frac{2}{3}\log_{10} M_o - 10.7 \quad (2)$$

where $\mu = 3.0 \times 10^{10}$ N/M is the rigidity of earth mantle, D is the amount of slip motion (slip) and L is the length of the fault plane and W is the width of the fault plane, M_o is the scalar moment of an earthquake and M_w is the moment magnitude of an earthquake. The calculated slip motion on each fault plane segment is shown in the last column in Table 3.

With all the fault parameters shown in Table 3, the seafloor deformation over each fault segment can be computed via Okada's elastic fault model (Okada, 1985).

3. Simulation of tsunamis generated along Manila Trench

In this section, we analyze the tsunami arrival time and amplitude distribution using the hypothetical earthquake of magnitude $M_w = 8.0$ with the fault plane parameters as listed in Table 3. The simulated results will help to identify the correlation between most affected coastal areas with the fractured fault plane segment. The arrival time analysis will also provide important information in selecting the locations of tsunami deep-ocean sensors.

In simulating tsunami propagations, we first assume that the initial sea surface profile mimics the final seafloor deformation after the earthquake. This is reasonable since the duration of an earthquake is usually very short and the size of the rupture area is very large compared to the water depth. Therefore, there is not enough time for the water above the seafloor deformation to drain out. Tsunami propagations are simulated with a validated numerical model – COMCOT, which uses an explicit Leap-Frog finite difference scheme to solve the Shallow Water Equations (Liu et al., 1994, 1995, 1998). In this study, uniform 2-min grids using bathymetry data from ETOPO2, are implemented for all the simulations. The numerical domain ranges from 99°E to 133°E in longitude and 1°S–33°N in latitude with a grid dimension 1021 × 1021 (see Fig. 4). A vertical wall boundary is assumed along shorelines, where water depth is 5.0 m.

3.1. Arrival time and tsunami amplitude distribution

In Fig. 5 the contours of arrival time are plotted for different tsunami scenario corresponding to rupturing different fault plane segment. In this paper, the arrival time is defined as the instant when the water surface is elevated more than 1 cm above the mean sea level due to the arrival of the leading tsunami wave. In regions where tsunami waves are relatively high, this criterion works very well. However, in regions far from the source area and where tsunami wave amplitude is very small (close to 1 cm), especially where bathymetry is complicated as well (with islands, submarine

[1] For interpretation of color in Figs. 2, 3, and 9 the reader is referred to the web version of this article.