NUMERICAL SIMULATION OF TSUNAMI PROPAGATION AND INUNDATION ALONG THE RAKHINE COAST AREAS IN MYANMAR

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ABSTRACT

This study aimed to assess the tsunami hazard at the Rakhine coast in Myanmar by tsunami propagation and inundation simulation considering a scenario earthquake along the Arakan Trench. We selected the location of the 8 tide gauge stations as the output points located in the Rakhine coast. Seven are assumed as tide gauge stations and one is an actual tide gauge station operated by the Myanmar government. To calculate the tsunami maximum wave heights and tsunami arrival times at the output points, we performed numerical simulations using TUNAMI-N2. We assumed a scenario earthquake (Mw 8.9) along the Burma subduction zone off the Rakhine coast. We used the 1 arc-minute and 30 arc-seconds GEBCO bathymetry data. The numerical modeling of tsunami propagation is based on a uniform grid system in cartesian coordinates. The numerical modeling of tsunami inundation is based on a nested grid system in spherical coordinates using non-linear theory with four different spatial grid sizes. The maximum tsunami height was around 1.4 m along the Rakhine coast. We performed tsunami inundation modeling around Sittwe City, and found a little tsunami inundation occurred in this area.

Keywords: Numerical simulation, Tsunami height, Tsunami arrival time, Tsunami inundation, Assessment, Arakan Trench.

1. INTRODUCTION

Myanmar is one of earthquake prone countries, which is situated on the boundary of the Alpide-Himalayan Earthquake Belt where devastating earthquakes have occurred from time to time. An active and long subduction (the Indo-Burma) zone lies near the Myanmar coastal areas. Thus, the Myanmar coastal areas are vulnerable to not only regionally but also distant tsunami. The earliest earthquake on record which affected the western coast of Burma (Myanmar) took place on 2nd April 1762 (e.g. Cummins, 2007). It was violent and felt all over Bengal, Arakan etc., chiefly and more severely in the northern part of the east of the Bengal Bay. The giant Sumatra earthquake on 26th December 2004, according to the information from tsunami surveys, the height of the wave arrived in Myanmar was from 0.4 m to 2.9 m (Satake et al., 2005). Although Myanmar had less fatalities and damages among the countries hit by the tsunamis of the 2004 Sumatra earthquake, it is clearly shown that Myanmar coastal areas are vulnerable to tsunami. Cummins (2007) also suggested that there is a high possibility of occurrence of a tsunamigenic earthquake in the northern Bay of Bengal near Rakhine coast which is a populated coastal area. A tsunami threat can significantly devastate this region. Therefore, numerical tsunami simulation is imperative to determine the travel time and height of tsunami that may affect the region. By knowing the tsunami characteristics that is expected to attack the region, a tsunami hazard planning can be made to mitigate its effect on the populated coastal areas of Myanmar.

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2. THEORY AND METHOD

2.1 Governing Equation in Cartesian Coordinate System

The fundamental equations of the continuity and momentum in two dimensions for the cartesian coordinate system are expressed below:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{\tau_x}{\rho} = 0 \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{\tau_y}{\rho} = 0 \tag{3}$$

where, M and N are the components of discharge fluxes in the x and y directions, η is the vertical displacement of water surface above the still water surface, t is the time, D is the total water depth, x and y are the horizontal axes, g is the gravitational acceleration, h is the sea depth,τ_x *and* τ_y are the bottom frictions in the x- and y- directions and ρ is the density.

2.2 Governing Equation in Spherical Coordinate System

It is necessary to use the spherical coordinate system in performing the numerical simulation to capture the globular shape of the earth. The continuity and momentum equations are expressed in the terms as follows:

$$\frac{\partial \eta}{\partial t} + \frac{1}{Rcos\theta}\left[\frac{\partial M}{\partial \lambda} + \frac{\partial}{\partial \theta}N(cos\theta)\right] = 0 \tag{4}$$

$$\frac{\partial M}{\partial t} + \frac{gD}{Rcos\theta}\frac{\partial \eta}{\partial \lambda} + \frac{1}{Rcos\theta}\frac{\partial}{\partial \lambda}\left(\frac{M^2}{D}\right) + \frac{1}{Rcos\theta}\frac{\partial}{\partial \theta}\left(cos\theta\frac{\partial MN}{D}\right) + \frac{gn^2}{D^{\frac{7}{3}}}M\sqrt{M^2+N^2} = 0 \tag{5}$$

$$\frac{\partial N}{\partial t} + \frac{gD}{Rcos\theta}\frac{\partial}{\partial \theta}(cos\theta\eta) + \frac{1}{Rcos\theta}\frac{\partial}{\partial \lambda}\left(cos\theta\frac{N^2}{D}\right) + \frac{1}{Rcos\theta}\frac{\partial}{\partial \lambda}\left(\frac{MN}{D}\right) + \frac{gn^2}{D^{\frac{7}{3}}}N\sqrt{M^2+N^2} = 0 \tag{6}$$

where, η is the wave amplitude, M is the discharge fluxes in the λ (along a parallel of latitude) direction, N is the discharge fluxes in the θ (along a circle of longitude) direction, R is the radius of the earth at 6378.137 km, t is the time, n is the manning roughness coefficient, g is the gravitational acceleration, D is the water depth, and $\frac{gn^2}{D^{7/3}}\ M\ \sqrt{M^2+N^2}$ and $\frac{gn^2}{D^{7/3}}\ N\ \sqrt{M^2+N^2}$ are the bottom friction term.

3. TSUNAMI NUMERICAL SIMULATION

3.1 Tsunami Simulation

We used the TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of the Near-field tsunami No.2) code, which was developed by Disaster Control Research Center (DCRC) Tohoku University, Japan (Koshimura 2013; Imamura et al., 2006), in order to simulate the generation and propagation of the tsunami wave considering a shallow water wave theory and bottom friction. The propagation and inundation were calculated by using the TSUNAMI-N2 code based on the cartesian coordinate and spherical coordinate systems.

3.2 Study Area and Target Area

Myanmar experienced the tsunami effect of the M 9.2 earthquake on 26th December 2004 Sumatra earthquake. After the Sumatra earthquake, some researchers (Cummins, 2007) pointed out the possibility of a potential tsunamigenic earthquake that may occur on the northern part of the Bengal Bay. If this tsunamigenic earthquake occurs, it will mostly affect the Rakhine coast that faces the Bengal Bay. Thus, a study of the characteristics of the tsunami that may devastate the Rakhine coast is imperative to the dense population of Sittwe City to mitigate the possible effect of tsunami wave. In this study, the computational domain ranges from 9°N to 25°N in Latitude and from 86°E to 99°E in Longitude.

4. DATA

4.1 Bathymetry Data for Tsunami Simulation

For the tsunami simulations, we used the 1 arc-minute bathymetry data and 30 arc-seconds bathymetry data from the General Bathymetry Chart of the Ocean (GEBCO) which can be downloaded from the website (http://www.bodc.ac.uk/data/online_delivery/gebco/). Table 1 shows a summary of the data and resolution used for the simulations.

Table1. Summary of bathymetry data and resolution used for simulation.

Bathymetry Data	GEBCO 1arc-min	GEBCO _08 30 arc-sec
Resolution	1 arc-min	1 arc-min
Grid dimension	780 × 960	780 × 960
Temporal Grid Size(dt)	3 s	3 s

4.2 Bathymetry and Topography Data for Tsunami Inundation Modeling

In order to perform the tsunami numerical modeling, the computational area is divided into four regions. The bathymetry data for four regions are interpolated from the General Bathymetry Chart of the Ocean (GEBCO) 30 arc-seconds grid data. For the calculation of inundation area, we obtained data from the Shuttle Radar Topography Mission (SRTM) retrieved from the Internet (http://dds.cr.usgs.gov/srtm/version2_1/SRTM3/Eurasia). The bathymetry and topography data for the four domains were interpolated from large region to small region. The topography data for the first to third domains were interpolated from the 30 arc-seconds GEBCO and for the fourth domain it was taken from the Shuttle Radar Topography Mission (SRTM) 3 arc-second resolution data as shown in Figure1.

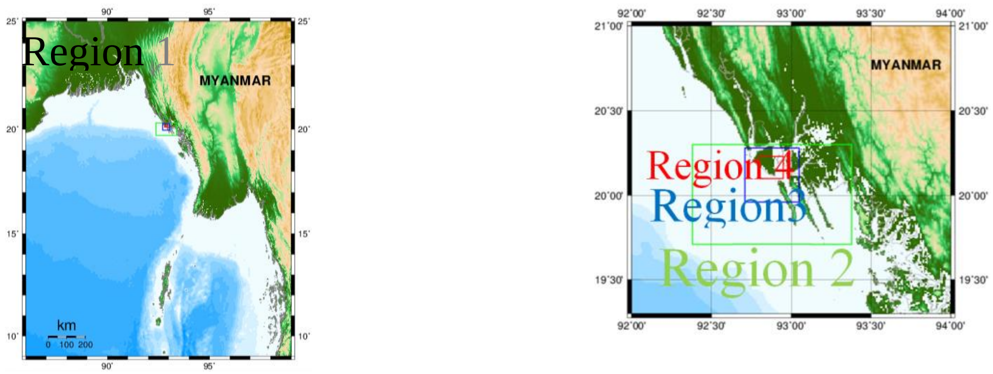

Figure1. Location and boundary for each computational domain in inundation. Left figure shows Region 1 and right figure shows Region 2 (green rectangle), Region 3 (blue rectangle) and Region 4 (red rectangle).

4.3Tide Gauge Stations

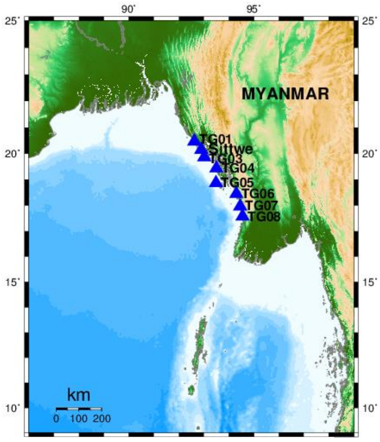

Figure 2. Location of the tide gauge stations.

In this study, we set the location of the 8 tide gauge stations along the west coast of Myanmar. Tsunami waveform was calculated at the 8 tide gauge stations to obtain the tsunami wave height and arrival time at each location as shown in Figure 2. Among these 8 tide gauge stations, we assumed the 7 tide gauge stations and set them in the important places along the study area. One tide gaugestation (Sittwe) is an actual tide gauge station operated by Myanmar.

5. RESULT AND DISCUSSION

5.1 Computational Dimension and Source of Scenario Earthquake for Simulation

In this study, we used the computation region used for the earthquake scenario as shown in section 4.1 and Table 1. The spatial grid interval Δx was 1,774 m and Δy was 1,844 m for the 1 arc-minute GEBCO and 30 arc-seconds GEBCO data resolutions. In order to stabilize the numerical computation, the temporal grid sizes *(Δt)* were set at 3.0 s for uniform grid computation in the 1 arc-minute bathymetry data and 30 arc-seconds bathymetry data which satisfies the Courant-Friedrich- Lewy (CFL) condition. The total duration of the calculation was 3 hours and had time steps of 3,600 for computational time in uniform grid simulations using the 1 arc-minute bathymetry data simulation and 30 arc-seconds bathymetry data simulation. The maximum water depth (h_{max}) was 4,222.05 m in the 1 arc- minute GEBCO and 4,416.93 m in the 30 arc seconds GEBCO.

We used the source parameters for the scenario earthquake by Oo Than (2010). We assumed the depth as 0 km (depth of the top edge corner of the fault).

Table 2. Source parameters of scenario earthquake at the Arakan Trench.

Lat (°N)	Long (°E)	Length (km)	Width (km)	Strike (°)	Dip (°)	Rake (°)	Slip amount (m)	Top depth (km)
17.00	93.9375	358.794	172.811	341	10	127	7.67	0

5.2 Maximum Tsunami Heights

From the tsunami simulation, we obtained tsunami waveforms and the maximum tsunami wave heights as well as the tsunami arrival times at 7 assumed and 1 actual (Sittwe) tide gauge stations. Using the TUNAMI-N2 code, we estimated the tsunami wave heights in every time step for coastal output points with the scenario. From the simulation using 1 arc-minute GEBCO, we obtained the highest tsunami wave height of 1.48 m at TG07 and the second highest tsunami wave height of 1.45 m at TG06. The 3 tide gauge stations (TG03, TG04 and TG08) had the maximum tsunami wave heights from 1 m to 1.3 m and TG 01, Sittwe and TG05 recorded waves of less than 1 m. From the simulation using the 30 arc-seconds GEBCO, we obtained the highest tsunami wave height of 1.40 m at TG05 and the second highest tsunami wave height of 1.37 m recorded at TG07. The maximum tsunami wave heights at 5 tide gauge stations (TG01, TG03, TG04, TG06 and TG08) were between 1 m and 1.4 m and Sittwe tide gauge station recorded a maximum tsunami wave height of 0.57 m.

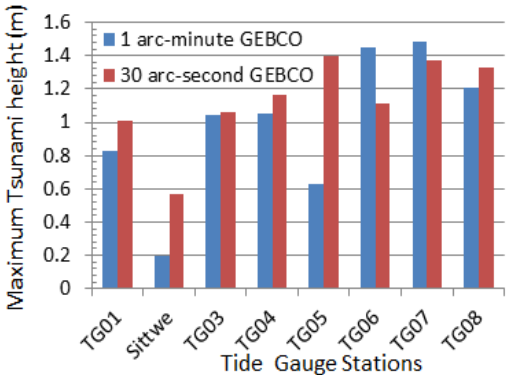

Figure 3. Comparison of the maximum tsunami heights obtained through a numerical simulation using TUNAMI-N2 code for coastal output points with different bathymetry data the 1 arc-minute and 30arc-seconds.

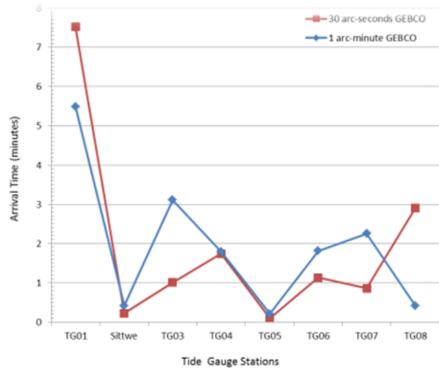

Figure 4. Tsunami arrival time calculated at each tide gauge station for the tsunami source using the 1 arc-minute and 30 arc-seconds bathymetry data.

5.3Tsunami Travel Time

We derived the tsunami arrival times from the waveforms recorded at each tide gauge station as shown in Figure 4. Tsunami arrived in a few minutes at all tide gauge stations after occurrence of the earthquake as calculated using the GEBCO 1 arc-minutes and GEBCO 30 arc-seconds datasets because of its close proximity from the tsunami source. Two output points located in a subsidence area computed a negative tsunami waves using the 1 arc-minute GEBCO and 30 arc-seconds GEBCO. Positive waves reached the 6 output points in different time depending on the distance of the output points from the tsunami source. Tsunami arrival time did not change much in the simulation with the grid resolution of the 1 arc-minute and the grid resolution of 30 arc-seconds.

5.4Tsunami Inundation

The tsunami inundation is calculated on the fourth domain using the bathymetry of the 30 arc-seconds uniform grid and topography grid data (see Figure 1), and in this domain there were 780 and 960 grid points along the latitude and longitude directions, respectively, for which the computation time was 3 hours which had time steps of 10,800 for the nested grid simulation. In order to stabilize the numerical computation, temporal grid size (Δt) was set to 1.0 s for the nested grid computation, which satisfies the CFL condition.

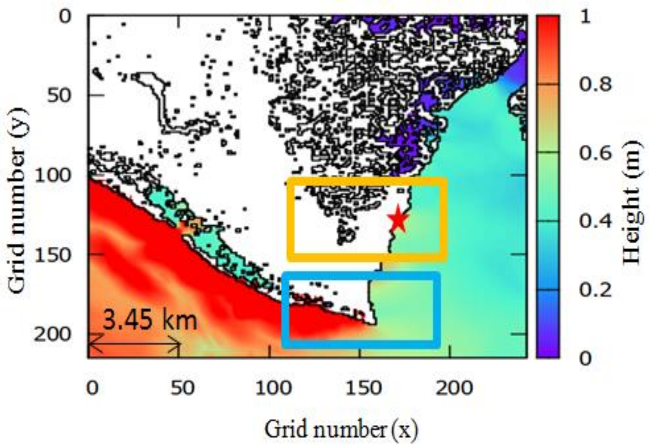

Figure 5. Tsunami heights obtained from tsunami inundation simulation for region 4.

Figure 5 shows a result of tsunami inundation modeling around Sittwe City. Yellow and blue rectangle areas are magnified in Figures 6 and 7. Inside of the blue rectangle, the maximum tsunami height in inundation areas reached around 1 m (Figure 7). Populated area in Sittwe City is located in the yellow rectangle. The highest tsunami wave height of 0.75m was calculated at the coast line (Sittwe City). However, there was a little inundation in Sittwe City obtained from the simulation.

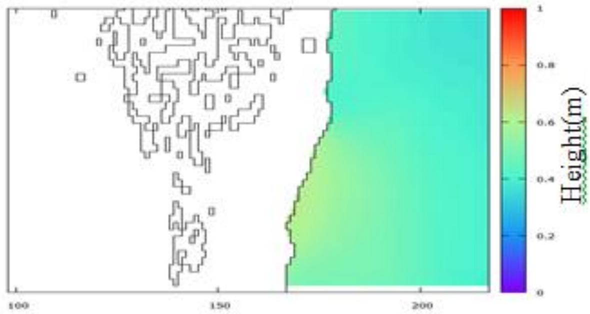

Figure 6 . Magnified view around Sittwe City shown in the yellow rectangle in Figure 5.

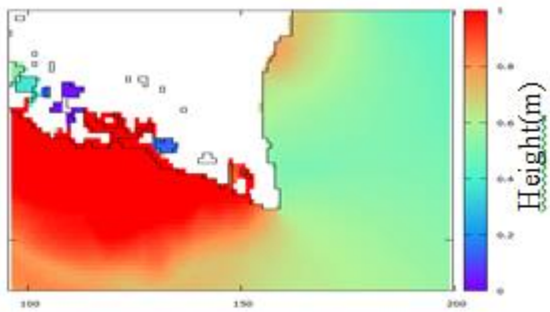

Figure 7. Magnified view southern part of Sittwe City shown in the blue rectangle in Figure 5.

6. CONCLUSION

We performed numerical simulation of tsunami propagation along the Rakhine coast in Myanmar by assuming a scenario earthquake (Mw 8.9) along the Burma subduction zone. The results show that the maximum tsunami height is around 1.4 m along the Rakhine coast. The maximum tsunami wave height using the 30 arc-seconds bathymetry data except the tide gauges TG06 and TG07 was higher than that using the 1 arc-minute bathymetry data. The patterns of the maximum tsunami wave height were not similar in 1 arc-minute bathymetry data and 30 arc-seconds bathymetry data. This is probably because of the characteristics of the ocean bottom topography and the tsunami energy directivity.

We calculated tsunami arrival time at each tide gauge stations. The tsunami wave arrived within a few minutes at all tide gauge stations after occurrence of the earthquake as calculated using the GEBCO 1 arc-minutes and GEBCO 30 arc-seconds datasets because of its close proximity from the tsunami source.

We also performed tsunami inundation modeling around Sittwe City. The highest tsunami wave of 0.75 m was calculated at the coast line of Sittwe City. There was a little inundation calculated in the city obtained from the simulation.

According to the tsunami simulation results from this study, there is a threat of tsunami to the Rakhine coast. In order to obtain more consistent and better results for the tsunami inundation computation, the use of detailed and accurate bathymetry as well as topography data is essential in a small grid size, which is much more effective in the numerical computation. The local communities living in the areas with vulnerabilities should have the awareness about tsunami disaster.

My future work plans include formulation of a tsunami hazard map based on the result of my study and to prepare tsunami evacuation plan for the coastal communities to protect them from the tsunami effects. I also would like to continue tsunami simulation and inundation modeling for other tsunami prone areas along the Myanmar coast.

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