TSUNAMI INUNDATION MODELING ALONG THE EAST COAST OF SABAH, MALAYSIA FOR POTENTIAL EARTHQUAKES IN SULU SEA

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ABSTRACT

A tsunami numerical inundation modeling in the east coast of Sabah was developed by considering large earthquakes along the Sulu Trench as the tsunami source. The simulation was conducted using modified TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near Field Tsunami, No. 2) with a nested grid system in spherical coordinate system. Nonlinear shallow water theory with bottom friction with four different spatial grid sizes was used in the computation. Three scenarios of different magnitudes, M_w 8.2, M_w 8.5 and M_w 8.8 were assumed. The results showed that in Tambisan Island the first tsunami wave arrived 22.5 min after the earthquake with maximum tsunami height of 8.6 m and tsunami run-up of 10.1 m in Scenario 3 (M_w 8.8). In Sandakan, the first tsunami arrived 93 min after the earthquake with maximum tsunami height of 3.8 m and tsunami run-up of 4.0 m in Scenario 3 (M_w 8.8). These results show that Tambisan Island and Sandakan have a risk of tsunami threat from megathrust events along the Sulu Trench.

Keywords: Tsunami simulation, Inundation, Sulu Trench, Sabah, Sandakan, Tambisan Island.

1. INTRODUCTION

A tsunami is a natural disaster that occurs as a result of the earthquakes in the subduction zone. Although seismicity is considered low in Malaysia and Malaysian oceans are also considered less vulnerable to tsunami; nevertheless it can still occur depending on several factors such as the magnitude of earthquakes, features of the seabed bathymetry, tectonics settings, and many others. The east coast of Sabah may be affected by large earthquakes along the Sulu Trench, which is capable of producing tsunamis. There were historical tsunamis recorded along this subduction zone, and at least two tsunamigenic earthquakes occurred near the Sulu Trench region. The east part of Sabah is sparsely populated, but its population is predominant in the coastal area. There are water villages along the coast which increase the vulnerabilities when tsunami occurs in the Sulu Sea.

Mazni (2011) has demonstrated that the largest tsunamis at eastern coast of Sabah can be caused by large earthquakes along the Sulu Trench. Hence, this study is to develop an inundation model from the trans-oceanic tsunami in the Sulu Sea using a nested grid system in the spherical coordinate system. This is required in order to assess the potential of tsunami impact from any future Sulu Trench earthquakes. This study also is aiming to investigate the maximum tsunami heights and tsunami arrival times at the eastern coast of Sabah.

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2. DATA

2.1. Tsunami Simulations, Bathymetry and Topography Data

Tsunami simulation is performed using simulation code which is developed by Yanagisawa (2012) based on the TUNAMI-N2 in nested grid system. Nonlinear shallow water theory with bottom friction in the form of Manning's formula is applied in the computation. Bathymetry and topography data for the first to third region are taken from the General Bathymetric Chart of the Ocean (GEBCO) (https://www.bodc.ac.uk/data/online_delivery/gebco/) 30 arc-second (resampling to 1 min grid size). Bathymetry and topography for the fourth region are interpolated from the nautical chart (Ridzuan, 2010) and Shuttle Radar Topographic Mission (SRTM) (http://www2.jpl.nasa.gov/srtm/). Table 1 shows the boundary, resolution, location and data source for each region.

Table 1. Boundary, resolution and data source for each computational region.

Region		Longitude		Latitude		Grid Size		Data Source	
		Min	Max	Min	Max	Spatial	Temporal	Bathymetry	Topography
1		115^o	123^o	2^o	10^o	1'	2"	GEBCO 30"	GEBCO 30"
2		$117^o30'$	$119^o30'$	5^o	$6^o30'$	20"	0.6667"		
3	a	$118^o45'$	$119^o20'$	$5^o15'$	$5^o45'$	6.6667"	0.2222"		
	b	$117^o55'$	$118^o20'$	$5^o40'$	$6^o05'$				
4	a	$119^o03'$	$119^o11'$	$5^o25'$	$5^o30'$	2.2222"	0.0740741"	Nautical Chart	SRTM 3"
	b	$118^o03'$	$118^o09'$	$5^o51'$	$5^o55'$				
	c	$118^o02'$	$119^o08'$	$5^o47'$	$5^o51'$				

Total computation time is 360 min which has the time steps of 10,800. Tsunami waveform is calculated at several assumed tide gauge stations along the Tambisan Island and Sandakan coast to obtain tsunami height and arrival time. For inundation modeling, several assumed coastal points have been selected on land in the target areas.

2.2. Scenario Earthquakes in the Sulu Trench

In the present study, multi-segment earthquake from the Sulu Trench are taken as an earthquake source of which top depth is assumed to be 1.0 km for all scenarios. The parameters used here are proposed by Salcedo (2010) with trench segmentation given by Bautista (2001). Three scenarios are investigated in this study. Two more earthquakes of magnitude Mw 8.5 (with a slip of 10 m) and Mw 8.8 (with a slip of 20 m) are assumed as the worst case scenarios. Table 2 describes the parameters for each scenario.

Table 2. Faults parameters for each scenario earthquake.

Scenario	Source	M_w	Fault Location		Length	Width	Strike	Dip	Rake	Slip
			Long	Lat	(km)	(km)	(deg)	(deg)	(deg)	(m)
1	ST1	8.2	121.4	7.2	167	71.97	30	45	129	2.26
	ST2		119.6	6.2	230	84.00	60	45	90	3.16
2	ST1	8.5	121.4	7.2	167	71.97	30	45	129	10.0
	ST2		119.6	6.2	230	84.00	60	45	90	10.0
3	ST1	8.8	121.4	7.2	167	71.97	30	45	129	20.0
	ST2		119.6	6.2	230	84.00	60	45	90	20.0

3. THEORY AND METHODOLOGY

3.1. Shallow Water Theory

A spherical coordinate shallow water model has been applied to simulate the propagation of tsunami originated from the Sulu Trench. It can express as follows (Dao and Tkalich, 2007):

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

$$\frac{\partial M}{\partial t}+\frac{gD}{R\cos\theta}\frac{\partial \eta}{\partial \lambda}+\frac{1}{R\cos\theta}\frac{\partial}{\partial \lambda}\left(\frac{M^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial \theta}(\cos\theta\frac{MN}{D})+\frac{\tau_{bx}}{\rho}=0 \quad (2)$$

$$\frac{\partial N}{\partial t}+\frac{gD}{R\cos\theta}\frac{\partial}{\partial \theta}(\cos\theta\eta)+\frac{1}{R\cos\theta}\frac{\partial}{\partial \lambda}\left(\cos\theta\frac{N^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial \lambda}(\frac{MN}{D})+\frac{\tau_{by}}{\rho}=0 \quad (3)$$

where θ and λ are the latitude and longitude respectively, η is elevation of water surface, D is still water depth and R is the earth rotation. M and N are the components of discharge along the latitude θ and longitude λ. $\frac{\tau_{bx}}{\rho}$ and $\frac{\tau_{by}}{\rho}$ are the bottom friction terms express as $\frac{\tau_{bx}}{\rho}=\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}$ and $\frac{\tau_{by}}{\rho}=\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}$ respectively (Imamura, 2006).

4. RESULTS AND DISCUSSION

4.1. Tsunami Propagation

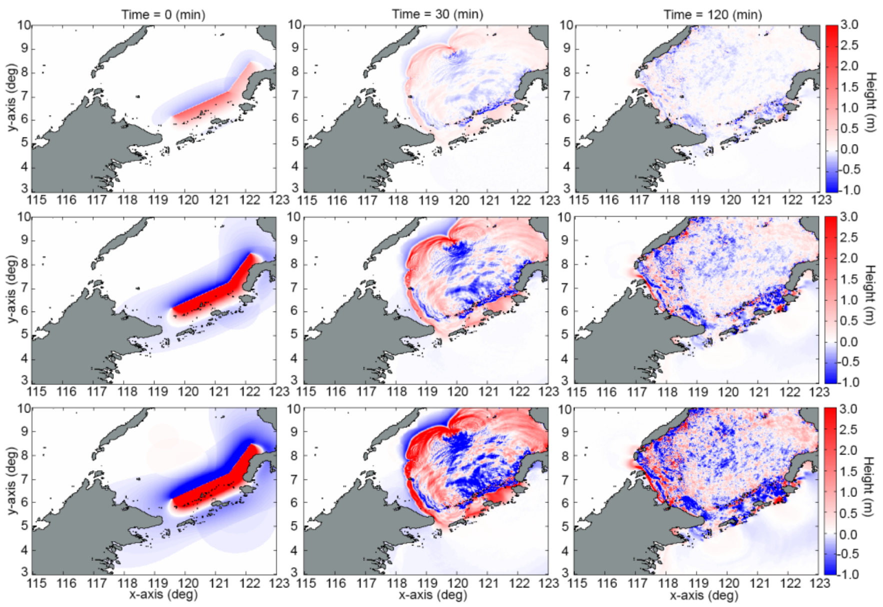

Figure 1. Snapshot of tsunami propagation at 0 min (initial time), 30 min and 120 min for all scenarios.

Figure 1 shows the snapshot of tsunami wave propagation generated from a multi-segment fault along the Sulu Trench for each scenario. The initial waves for each scenario are shown in the left panel while the other two panels show the snapshots of tsunami propagation at 30 and 120 min after the earthquake. The first wave reaching the Sabah coast for all scenarios is the negative wave.

In Scenario 1 (M_w 8.2), the positive wave reaches Sabah in Tambisan Island approximately 35 min after the earthquake. In less than 1 hour after the earthquake, tsunami wave reaches the entire coast of Tambisan Island in all scenarios. Then tsunami wave continues to propagate in the Sulu Sea and reaches the water village in the eastern Sandakan (in Region 4b) at approximately 1 hour 38 min after the earthquake occurred. For the earthquake of magnitude M_w 8.5 (Scenario 2) and M_w 8.8 (Scenario 3), the tsunami wave height is higher compared to Scenario 1 (M_w 8.2). The difference in magnitude of the earthquake in this study does not influence much to the tsunami arrival time in all scenarios.

4.2. Maximum Tsunami Heights and Travel Times

Tsunami waveforms and the travel times are obtained from the tsunami simulation. We assumed 19 tide gauges which are located near the coastal area. Figure 2 shows the maximum tsunami height at each assumed tide gauge station for all scenarios. TBN5 recorded the maximum tsunami height in Tambisan Island for all scenarios as the wave concentrates along the coastline which has a characteristic of shallow circular bay. Tsunami wave height is about double in parallel with the increase in earthquake magnitude. In Sandakan, SDN1 always recorded the maximum tsunami height for all scenarios. SDN1 recorded a wave height of 1.0 m, 2.2 m and 3.8 m for Scenario 1, 2 and 3 respectively. The nearest assumed tide gauge to the Sandakan City is SDN5 which has the maximum tsunami height of 1.6 m in Scenario 3. The coast of Sandakan City has a threat from tsunami wave height of 1.0 m in Scenario 2. The nearest assumed tide gauges to the Sandakan Port is SDN 6a and it recorded a tsunami height of 2.1 m in Scenario 3. SDN 7 to SDN 8a represented Sandakan Industrial Zone which is located along the coast near the Sandakan Port, recorded maximum tsunami height of 1.0 m to 1.2 m in Scenario 3.

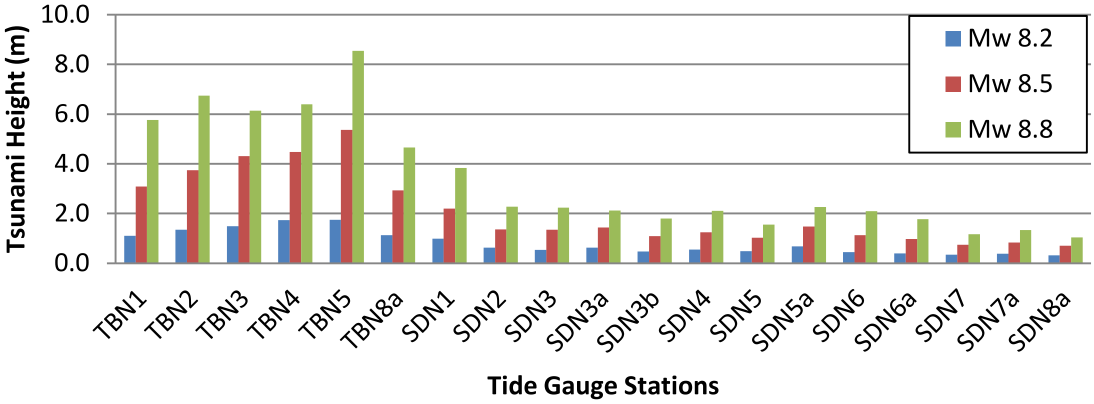

Figure 2. Maximum tsunami heights at each assumed tide gauge for all scenarios.

The earliest positive wave reaches the Sabah coast at 22.5 min (in Scenario 1, M_w 8.2) as recorded by assumed tide gauge TBN1 and the tsunami waves further propagate and surround the Tambisan Island. TBN1 recorded the earliest arrival time of positive wave for all scenarios in Tambisan Island. In all scenarios, tsunami waves hit Tambisan Island coast in less than 30 min after the earthquake. In Sandakan however, it takes more than 1 hour 30 min for the first positive wave to reach the assumed tide gauge SDN3b in the Sandakan coast. The waves propagate further to the north-westward and south-westward of the Sandakan coast. SDN3b recorded the earliest arrival time of positive wave for all scenarios in Sandakan.

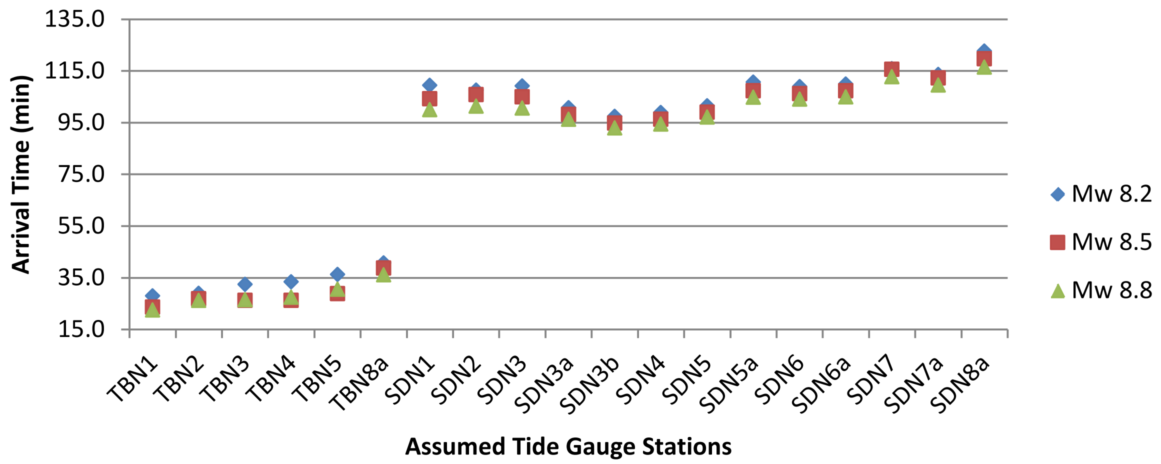

Figure 3. Estimated arrival times of positive tsunami wave at each assumed tide gauge station for all scenarios.

4.3. Tsunami Run-up Height and Inundation Area

Computed tsunami run-up height is calculated at the coastal points in Tambisan Island and Sandakan. The computed tsunami run-up heights at these selected coastal points are shown in Figure 4. The computed tsunami run-up heights in Tambisan Island exceeded 10.0 m at coastal point 3 for the worst case scenario (M_w 8.8). The same location records a run-up height of 5.85 m in Scenario 2 (M_w 8.5). The largest run-up height is recorded in this area among all the selected points in Tambisan Island for all the scenarios except for Scenario 1 (M_w 8.2), where the computed run-up height is 2.06 m. This is due to the wave concentrated along the coastline which has a characteristic of shallow circular bay and caused higher run-up. The height of run-up decreases as the wave propagates to the entire island in all scenarios, as recorded at coastal points 4 and 5.

The largest computed tsunami run-up height in Sandakan is recorded at coastal point 9 in Berhala Island beach for all scenarios. The computed run-up height is 1.36 m in Scenario 1 (M_w 8.2), 2.78 m in Scenario 2 (M_w 8.5) and 4.75 m in Scenario 3 (M_w 8.8). The existence of this island reduced the impact of tsunami waves that hit Sandakan Bay. Coastal points 7 and 10 represent the water villages along the coast in Sandakan Bay. Assuming a megathrust earthquake in the Sulu Trench (Scenario 3, M_w 8.8), the computed tsunami run-up height is 2.48 m and 2.57 m at points 7 and 10 respectively. In Sandakan city (represented by coastal point 11), the computed tsunami run-up height is 2.10 m. Coastal point 6 represents the closest location to the Sandakan Airport and recorded a tsunami run-up height of 4.04 m in Scenario 3 (M_w 8.8). At the other locations such as the Sandakan Port and the Sandakan Industrial Zone (represented by coastal points 13 and 14) which are located adjacent to the port along the Sandakan coast, a computed tsunami run-up height of less than 2.0 m is recorded for all scenarios.

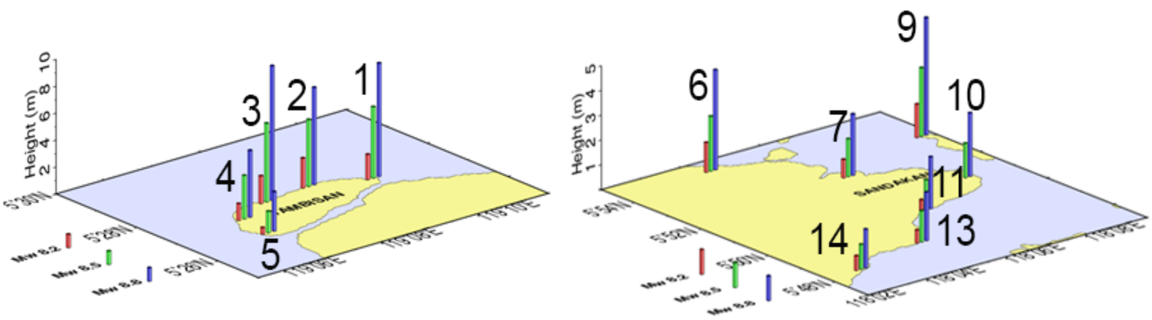

Figure 4. Computed tsunami run-up heights in Tambisan Island (left) and Sandakan (right) at coastal points labeled with numbers for all scenarios.

Figure 5 shows the inundation areas for Scenario 3 (M_w 8.8) in Regions 4a, 4b and 4c. The shape of inundated area is similar to those simulated in Scenarios 1 and 2, but the coverage is more extensive, and the maximum inundation height is higher. In Scenario 3, almost the entire coasts of Tambisan Island are inundated by the tsunami wave. The water villages in Region 4b might be severely damaged in Scenario 3 with the inundation reaching 2.0 m in height. Sandakan City and Sandakan Port are inundated by tsunami wave of more than 1.0 m height in Scenario 3 with extensive inundated area and the inundation height reaching almost 2.0 m. The Sandakan Industrial Zone which is located along the coast near Sandakan Port is highly affected by the tsunami wave.

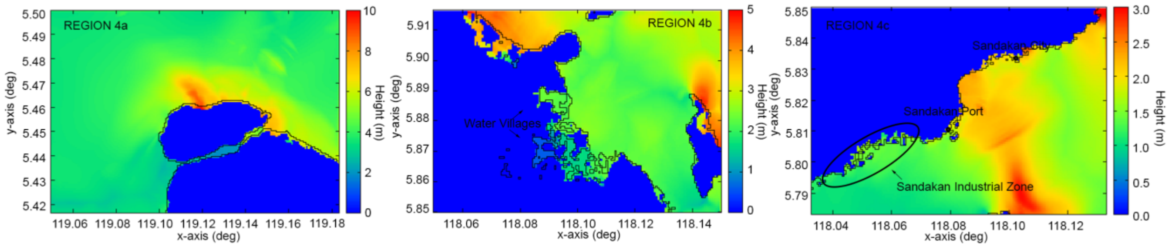

Figure 5. Inundation areas for Scenario 3 (M_w 8.8) in Regions 4a, 4b and 4c.

5. CONCLUSIONS

The simulated results show that the Tambisan Island coastline was at risk of tsunami threat with maximum tsunami wave height of at least 4.7 m in Scenario 3. In the simulation, Sandakan experienced much smaller tsunami waves of about 2.0 m for all scenarios. Average maximum tsunami height in water villages along the Sandakan coast is about 2.0 m in Scenario 3. The Sandakan coast near the airport experienced extensive inundated area, about 800 m distance from the coastline in Scenario 3. Sandakan city experienced tsunami waves with a maximum height of 1.6 m and maximum run-up height of 2.1 m. The inundation distance was about 300 m in Scenario 3. It is finally concluded that the east coast of Sabah faces the risk of tsunami threat from large earthquakes along the Sulu Trench.

6. RECOMMENDATION

There are still wide-ranging prospects in enhancing tsunami simulation based on the nested grid system in this study, and we suggest the following:

i. The bathymetry and topography data could be more detailed in grid size in order to improve the computed result of tsunami wave height, travel time, inundation height and distance,
ii. Sea bottom topography should be taken into consideration as well as the inland vegetation and structures such as building, etc.

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