TSUNAMI NUMERICAL SIMULATION AROUND SULU SEA AND CELEBES SEA

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ABSTRACT

We conducted tsunami numerical simulations around the Sulu Sea and the Celebes Sea using a modeling code called TUNAMI-N2. We investigated six scenarios for faults along the Negros Trench (2 segments), Sulu Trench (2 segments) and the Cotabato Trench (2 segments). We compared simulated results in numerical models based on a uniform grid in Cartesian coordinate system between using two bathymetry data, namely 1 arc-minute bathymetry data and 30 arc-second bathymetry data from GEBCO. The simulated results show that the maximum tsunami heights for simulations using 30 arc-second bathymetry data are mostly larger than those for simulations using 1 arc-minute bathymetry data. There is a threat of tsunami to the eastern coast of Sabah from an earthquake event of Mw 8.3 along the Sulu Trench with the maximum tsunami height of more than 1 m. Besides, Sabah may experience much smaller waves, of about less than 0.5 m for the tsunami source from the Negros Trench and the Cotabato Trench. This is because of two factors such as attenuation at wide shallow continental shelf and existence of small islands. The biggest maximum tsunami height at the Philippines coast is more than 4 m at Bayawan in case of the tsunami source from the Negros Trench. The tsunami arrives earlier for tsunami simulations using 30 arc-second bathymetry data than those using 1 arc-minute bathymetry data for all tide gauge stations except Lahad Datu, Tambisan, Bataraza and Bayawan. Detailed and accurate bathymetry data at shallower regions and near the coast are important to get reliable and much better results for tsunami computations.

Keywords: Tsunami, Maximum tsunami heights, Tsunami arrival times, Sulu Sea, Celebes Sea.

1. INTRODUCTION

Tsunami is one of the most devastating natural coastal disasters. Malaysian waters are comparatively less exposed to the threat of tsunami but there are many factors to allow the tsunami effects which may occur depending on the magnitude of the earthquakes, features of the seabed bathymetry, tectonics boundary between the ocean and the land, and many others. The east coast of Sabah region tends to be affected by tsunami hazards from earthquakes along the Negros Trench, Sulu Trench and the Cotabato Trench. There are historical earthquakes in these subduction zones that caused tsunami (http://www.ngdc.noaa.gov). The purpose of this study is to conduct simulations of the trans-oceanic propagation of tsunami in the Sulu Sea and Celebes Sea, and to investigate the maximum tsunami heights and tsunami arrival times at eastern coast of Sabah and several areas at the Philippines coast. This study also is aiming at investigation of the effect of maximum tsunami heights and tsunami arrival times due to different bathymetry data and different resolution of computation.

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2. DATA AND METHODOLOGY

2.1 Bathymetry data for tsunami simulations

TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis, No.2) codes are used in this study. TUNAMI-N2 codes were originally developed in the Disaster Control Research Center (DCRC), Tohoku University, Japan. The model has been implemented widely for tsunami simulation and run-up for the Tsunami Inundation Modeling Exchange (TIME) project (IUGG/IOC, 1997). The computation area is bounded by 2^{o}N to 14^{o}N in latitude and 115^{o}E to 127^{o}E in longitude (Figure 1). We used 1 arc-minute bathymetry data and 30 arc-second bathymetry data from General Bathymetry Chart of the Ocean (GEBCO) which can be downloaded from the website (https://www.bodc.ac.uk/data/online_delivery/gebco/). For each bathymetry data we elaborate two tsunami simulations, firstly with resolution of 1 arc-minute and secondly with resolution of 30 arc-second. The temporal grid sizes (dt) were set to 3.0 sec and 2.0 sec for resolution of 1 arc-minute and of 30 arc-second respectively which satisfied the CFL conditions to stabilize the numerical computation. The number of grid point is 720 x 720 for resolution of 1 arc-minute and 1440 x 1440 for resolution of 30 arc-second. The total duration of computation time is 6 hours. Table 1 shows a summary of the data used for simulations. Tsunami waveforms were calculated at 16 output points, of which 5 existing tide gauge stations are located around the coastal area of Sabah and 11 are assumed tide gauges along the eastern coast of Sabah and the Philippines coast (Figure 1).

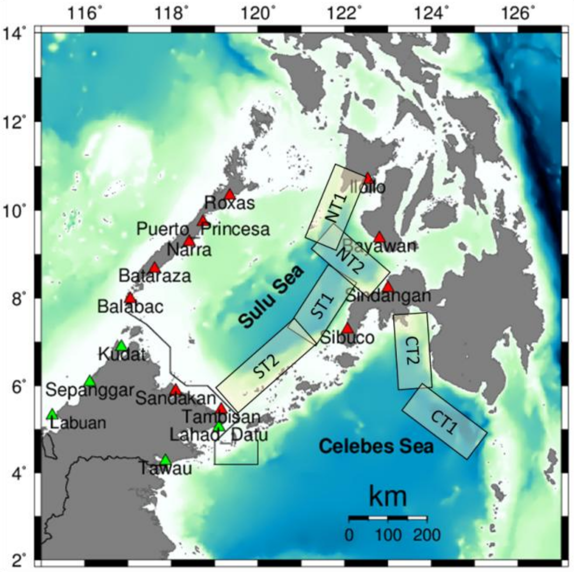

Figure 1. Computational area in numerical model. Locations of each segment represented by rectangular blocks. The green and red triangles represent the location of existing tide gauges and assumed tide gauges, respectively.

Table 1. Summary of data used for simulation

Name of the case	**Case a**	**Case b**	**Case c**	**Case d**
Bathymetry Data	GEBCO 1 arc-min	GEBCO 1 arc-min	GEBCO_08 30 arc-sec	GEBCO_08 30 arc-sec
Resolution	1 arc-min (1850 m)	30 arc-sec (925 m)	1 arc-min (1850 m)	30 arc-sec (925 m)
Grid dimension	720 x 720	1440 x 1440	720 x 720	1440 x 1440
Temporal Grid Size (dt)	3 s	2 s	3 s	2 s

2.2 Earthquake sources in the Philippines

The Philippines have experienced many earthquakes including some earthquakes that can cause tsunamis. For this study we used earthquake source parameters proposed by Salcedo (2010) from the Negros Trench (NT), Sulu Trench (ST) and Cotabato Trench (CT). Six cases of fault are investigated and the top depth of the fault is assumed to be 1.0 km for all cases. Table 2 shows a list of the parameters set for each segment in the Negros Trench, Sulu Trench and Cotabato Trench. The locations of each segment shown in Figure 1.

Table 2. Fault parameters for each scenario earthquake (Salcedo, 2010)

Number of Scenario	Source	Magnitude (M_w)	Location of the fault corner		Length	Width	Strike	Dip	Rake	Slip
			Long (^{o})	Lat (^{o})	(km)	(km)	(deg)	(deg)	(deg)	(m)
Scenario 1	NT1	8.2	121.5	9.0	206	81.01	20	32	100	2.89
Scenario 2	NT2	8.1	122.7	7.8	174	73.66	310	32	90	2.37
Scenario 3	ST1	8.0	121.4	7.2	167	71.97	30	45	129	2.26
Scenario 4	ST2	8.3	119.6	6.2	230	84.00	45	45	90	3.16
Scenario 5	CT1	7.9	124.5	4.9	135	63.84	315	25	79	1.77
Scenario 6	CT2	8.1	123.6	5.7	190	77.40	355	35	92	2.63

3. RESULTS AND DISCUSSION

3.1 Tsunami propagation

We investigate tsunami propagation considering four different cases as shown in Table 1 for 6 scenarios as shown in Table 2. Generally tsunami propagation in cases a and b are slightly different. Tsunami propagation in cases c and d also have slight differences. We noted that tsunami propagation in cases a and b is significantly different from cases c and d in several scenarios. This is caused by the fact that, the tsunami propagation path depends also on bathymetry data. Tsunami propagation in cases b and d is smoother than in cases a and c, because tsunami simulation in cases b and d used a grid resolution of 30 arc-second.

3.2 Maximum tsunami heights

3.2.1 Maximum tsunami heights for the tsunami source from the Negros Trench 1

For the tsunami source from the Negros Trench 1, the biggest maximum tsunami heights are calculated at Bayawan for all cases. This is because Bayawan is located very close to the tsunami source. At Bayawan, the maximum tsunami height for case 1a is 3.37 m while for case 1b it is 4.32 m. For cases 1c and 1d the maximum tsunami heights are 3.19 m and 3.77 m respectively at Bayawan. The maximum tsunami heights at Sabah coast were less than 0.5 m for all tide gauge stations while they were more than 0.5 m for tide gauges located at the Philippines coast except for Puerto Princesa and Balabac tide gauges. This is probably because of the characteristics of the sea bottom topography and the tsunami energy directivity. The maximum tsunami height is larger for simulations using 30 arc-second bathymetry data (cases 1c and 1d) except the tide gauges at Lahad Datu, Tambisan, Balabac and Bayawan compared with simulation using 1 arc-minute bathymetry data (cases 1a and 1b).

3.2.2 Maximum tsunami heights for the tsunami source from the Negros Trench 2

In case of the tsunami source from the Negros Trench 2, maximum tsunami heights more than 0.5 m were calculated at Bayawan, Iloilo (except for case 2b), Sindangan, Sibuco and Roxas (only for case 2d) while others show maximum tsunami heights less than 0.5 m. The biggest maximum tsunami height is 4.01 m at Bayawan for case 2d. This is because Bayawan is located close to the tsunami source. The maximum tsunami heights are lower at coastal areas of Sabah even though tsunami energy directly propagated to this area. This is due to a wide shallow continental shelf and existence of small islands such as Kagayan de Sulu Island, Nunuyan Island and Berhala Island facing to the Sabah coast. For this reason the tsunami heights will be reduced before arriving at the Sabah coast.

3.2.3 Maximum tsunami heights for the tsunami source from the Sulu Trench 1

For the tsunami source from the Sulu Trench 1, the biggest maximum tsunami heights were calculated for all cases at Sibuco. The maximum tsunami heights are 2.33 m for case 3c and 2.35 m for case 3d. The maximum tsunami height at Sibuco varies very much between two bathymetry data. In this case, when the bathymetry data was details or precise, the obtained maximum tsunami height was bigger. The difference in tsunami height is about two times. At Labuan tide gauge station, no computed tsunami heights were available. This is because of the location of Labuan at which much of the tsunami energy has been dissipated by the time tsunami waves approach to this area. Thus, we can conclude that Labuan is not an affected area if an earthquake generates a tsunami from the Sulu Trench 1.

3.2.4 Maximum tsunami heights for the tsunami source from the Sulu Trench 2

Figure 2 shows maximum tsunami heights for scenario 4 at each tide gauge station. It is observed that the maximum tsunami heights computed through simulations using 30 arc-second bathymetry data is larger than the one using 1 arc-minute bathymetry data except for stations of Lahad Datu, Tambisan, Balabac and Sindangan.

The biggest maximum tsunami height is calculated at Narra (about 2.4 m for case d). Other than that, at Roxas, Bataraza, Puerta Princesa and Sibuco were calculated the biggest maximum tsunami heights with the heights of more than 1.0 m in cases c and d. This is mainly because these stations are located directly along the path of the tsunami directivity. In view of the maximum tsunami heights at the Sabah coast, they were about 1.3 m at Tambisan in case a, and 0.73 m at Sandakan in case c while less than 0.5 m maximum tsunami heights calculated at other tide gauge stations. Sandakan may experience much smaller waves, of about 0.3-0.73 m even though it is located close to the source. This is due to a wide shallow continental shelf in Sabah coast and small islands such as Nunuyan Island and Berhala Island facing to the Sandakan.

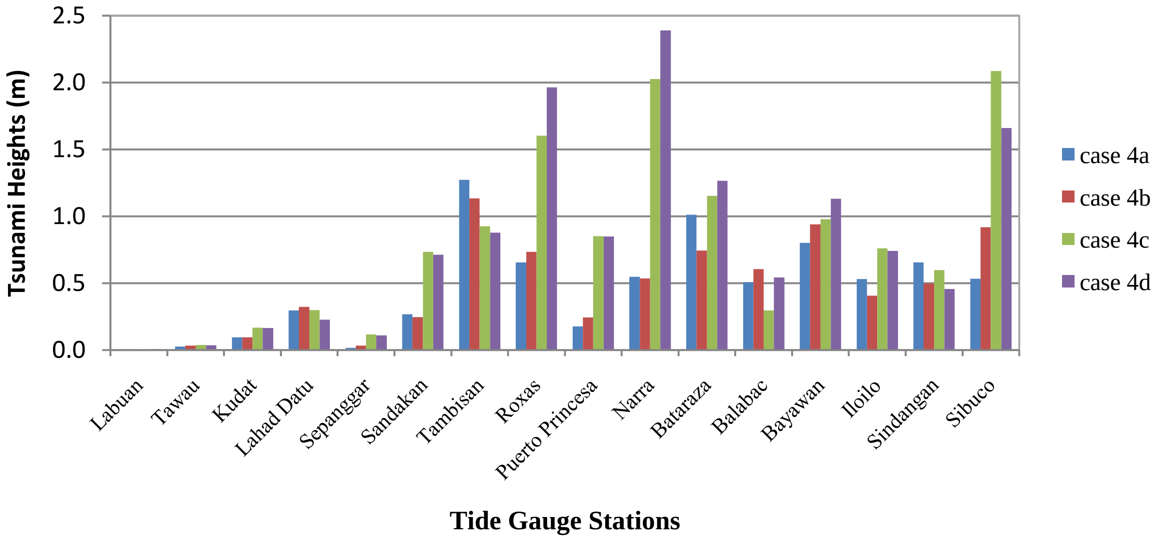

Figure 2. Maximum tsunami heights at each tide gauge for the tsunami source from the Sulu Trench 2.

3.2.5 Maximum tsunami heights for the tsunami source from the Cotabato Trench 1

The computed tsunami heights are very small at all tide gauge stations with less than 0.11 m for the tsunami source from the Cotabato Trench 1. This is because of small islands along stations of Sibuco to Tambisan as well as the tsunami energy directivity towards Sulawesi. The biggest maximum tsunami height calculated through this scenario is about 0.103 m (case c) at Lahad Datu.

3.2.6 Maximum tsunami heights for the tsunami source from the Cotabato Trench 2

For the tsunami source from the Cotabato Trench 2, the biggest maximum tsunami height is about 0.2 m (case 6d) at Lahad Datu. The maximum tsunami heights computed at Tawau and Tambisan are about 0.13 m (case 6a) and 0.17m (case 6c) respectively. We can conclude that tsunami generated from the Cotabato Trench 2 will not affect the eastern coast of Sabah area.

3.2.7 Comparison of maximum tsunami heights for all scenarios of case d

Figure 3 shows the maximum tsunami heights at each tide gauge station for case d with different scenarios (different sources of tsunami). As a result, the biggest maximum tsunami height was obtained at Bayawan station from scenario 2 with the tsunami source from Negros Trench 2. The Sabah coast may experience tsunami heights less than 0.5 m for all sources except for a tsunami source from the Sulu Trench 2 by which Sandakan and Tambisan may experience tsunami heights more than 0.5 m. It is observed that tsunami generated at the Cotabato Trench 1 (case 5d) and Cotabato Trench 2 (case 6d) would generate lower tsunami heights at each tide gauge station.

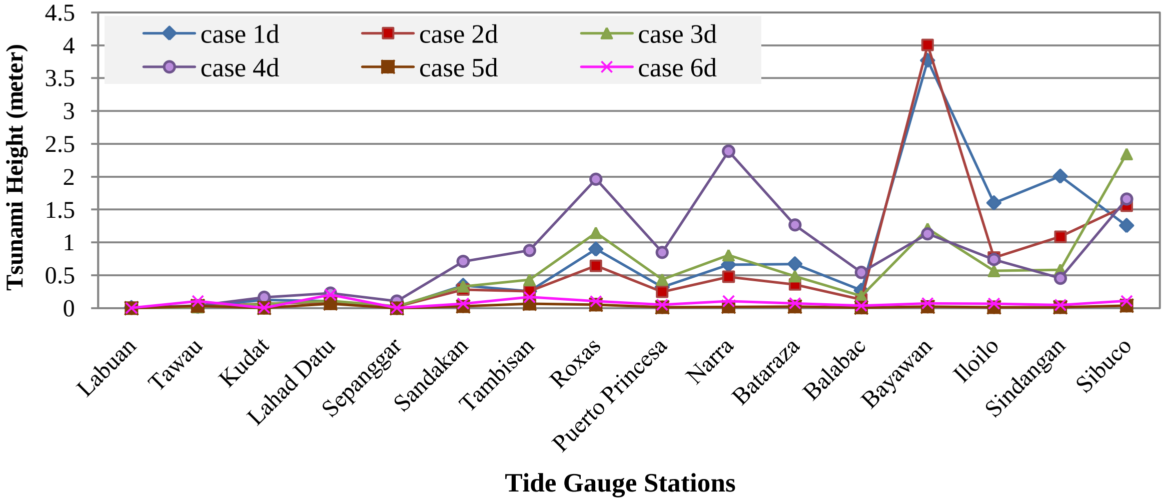

Figure 3. Maximum tsunami heights at each tide gauge station with different scenarios.

3.3 Tsunami arrival times

The tsunami arrival times were obtained at 16 output points along the Sabah coast and several areas at the Philippines coast. In this paper, the tsunami arrival time is defined as the beginning time of the first wave computed at tide gauge station. From this study, we find that tsunami arrived earlier for the tsunami simulations using 30 arc-second bathymetry data (cases c and d) than for those using 1 arc-minute bathymetry data (cases a and b) for all tide gauge stations except Lahad Datu, Tambisan, Bataraza and Bayawan. Tsunami arrival times did not change much in cases simulation with the grid resolution of 1 arc-minute and the resolution of 30 arc-second for the same bathymetry data.

Figure 4 shows the tsunami arrival times at each tide gauge station for case d with different scenarios (different sources of tsunami). As a result, tsunami will arrive at Iloilo, Sindangan and Sibuco just after the earthquake occurred at the Negros Trench 1, Negros Trench 2, and the Sulu Trench 1 respectively. At the Sabah coast, tsunami arrived earlier at Tambisan (less than 25 min) for the tsunami source from the Sulu Trench 2.

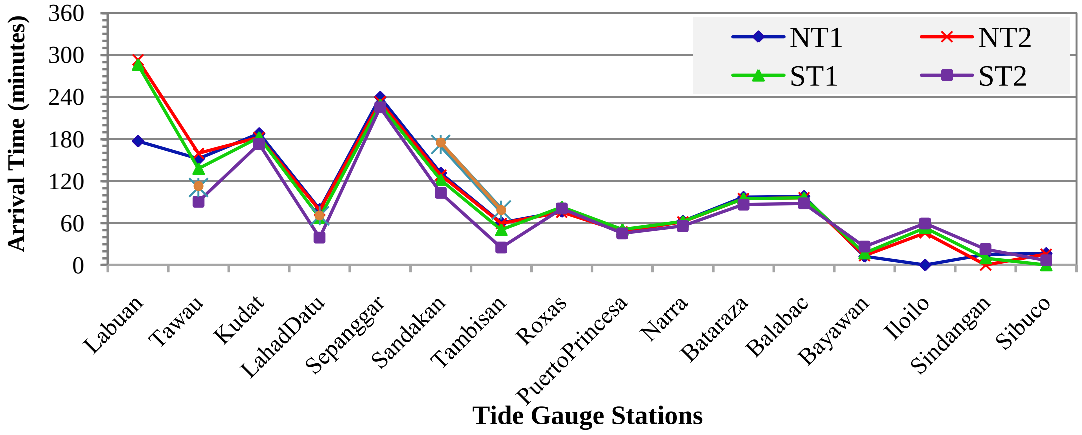

Figure 4. Tsunami arrival times at each tide gauge station with different scenarios.

4. CONCLUSIONS

The simulated results show that the biggest maximum tsunami height at Sabah coast is 1.271 m in case 4a (the tsunami source from Sulu Trench 2) at Tambisan while the biggest maximum tsunami height at the Philippines coast is 4.322 m in case 1b (the tsunami source from Negros Trench 1) at Bayawan. Sabah may experience much smaller waves, of about less than 0.5 m for all case scenarios (except Sandakan and Tambisan in scenario 4). This is because of two factors such as attenuation at wide shallow continental shelf and existence of small islands. The maximum tsunami heights for simulations using 30 arc-second bathymetry data (GEBCO_08) are mostly larger than those for simulations using 1 arc-minute bathymetry data (GEBCO).

The earliest tsunami arrival time is expected to be in less than 25 min at Tambisan in scenario 4 (the tsunami source from Sulu Trench 2). At the Philippines coast, tsunami will arrive just after the earthquake occurs in scenarios 1, 2 and 3 at Iloilo, Sindangan and Sibuco respectively. The tsunami arrives earlier for the tsunami simulations using 30 arc-second bathymetry data (case c and case d) than for those using 1 arc-minute bathymetry data (case a and case b) for all tide gauge stations except Lahad Datu, Tambisan, Bataraza and Bayawan. Tsunami arrival times do not change much in simulations with the grid resolution of 1 arc-minute and the resolution of 30 arc-second for the same bathymetry data.

It is finally concluded that, there is a threat of tsunami to the eastern coast of Sabah from Sulu Trench 2. However, detailed and accurate bathymetry data at shallower regions and near the coast are important to get more a reliable and much better result for tsunami computation. Hence, the residents living the vulnerable areas should be well prepared for the disaster.

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