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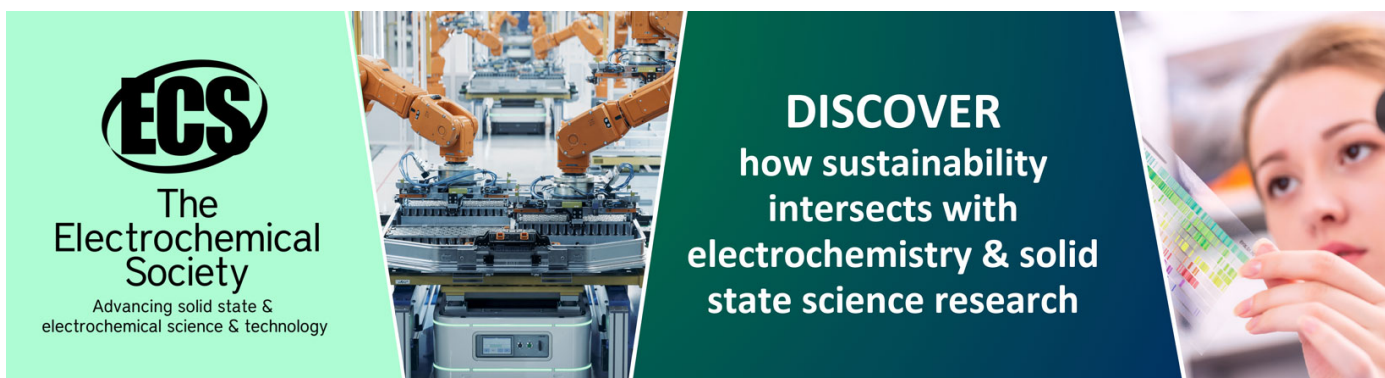
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Numerical simulations of land cover roughness influence on tsunami inundation in Ulee Lheue Bay, Aceh-Indonesia

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Abstract. Most of the flat area at Ulee Lheue Bay of Aceh Besar is affected by tsunami wave during the 2004 Indian Ocean Tsunami. The coastal area with no significant barrier caused tsunami wave inundating further inland. Coastal forest is known as an effective way to reduce tsunami impact in the coastal environment. In this paper, we used 2 Dimensional Horizontal (2DH) numerical model Cornell Multi-grid Coupled Tsunami (COMCOT) and Delft3D to evaluate the coastal forest influence which interpreted by variable Manning's coefficient of tsunami inundation. We also discussed the hydrodynamic characteristic of tsunami wave such as maximum water elevation and flow velocities to evaluate how effective is the coastal forest in reducing tsunami impacts at Ulee Lheue Bay. The results showed that the coastal forest effect is not significant difference both water elevation and tsunami inundation. Meanwhile, the coastal forest with 100 m width can reduce tsunami wave velocities about 40 %. It is important because high tsunami velocities caused severely eroded in the coastal area.

1. Introduction

Twelve years ago, the great Sumatera earthquake had shaken the Aceh Province with 9.1 Mw. A giant tsunami attacked the coastal area around the India Ocean that arrived in Sumatra's shores about 30 minutes after the earthquake [11]. Due to the tsunami waves, low lying areas of Aceh coastal zones were inundated by the tsunami waves. The tsunami caused major losses on human casualties and properties. After the tsunami, people started to realize how vulnerable Aceh coastal area toward tsunami. The dense of Aceh population around the coast amplified impacts on human casualties. Hence, we need to develop ways to reduce the impacts of the tsunami. Concept of coastal forest is known as an ecological method to reduce the impact of the tsunami on the coastal area. Unfortunately, the infrequent and unpredictable natural disaster of tsunami make it difficult to collect field research data of tsunami physical processes. Therefore, a numerical simulation is an important tool to better understand tsunami processes [3;9]. The information of tsunami hydrodynamics such as inundation area, flow depth and velocities will help coastal planners in improving tsunami hazard assessment to mitigate tsunami disaster.

Several studies have been conducted to focus on numerical simulation of tsunami hydrodynamic aspects including tsunami inundation, the effect of coastal forest, and land cover. For example, [4] used numerical simulation to investigate tsunami inundation and influence of land cover on flood patterns on the Andaman Sea coast of Thailand. Their study revealed flow velocities reduced up to 50

% by mangroves. Another study evaluated the reduction of tsunami inundation by coastal forest in Yogyakarta [7]. They found that the coastal forest with 100 m width reduced inundations flux, depth, and area by 17.6, 7.0 and 5.7 %, respectively. A study of the role of coastal forest on tsunami mitigation also has been conducted with field investigation. [2] argued that the coastal forest reduce tsunami disaster by stopping drifting materials or ships carried by a tsunami, to reduce tsunami energy, to form sand dune protecting tsunamis as well as high waves, and to catch persons brought back by a tsunami to the sea. All of the study areas mentioned above were located outside of Aceh Province. These motivate this study to particularly investigate the effect of land cover in Aceh where the 2004 Indian Ocean tsunami occurred.

This study is aimed at evaluating the damping effects of coastal forest width to reduce tsunami inundation that useful for mitigating future tsunamis in Ulee Lheue Bay. This study produced a detailed map of land cover in the study area derived from IKONOS imagery from January 2003 (before the tsunami). We set up another map of land cover for two scenarios with various width of coastal forest (mangrove) and fishpond. Scenario 1 and scenario 2 were set to have 50 m and 100 m of forest and fishpond, respectively. We focused on the coastal forest area. In the Delft3D numerical model, land cover information is interpreted by Manning coefficient (n) that was adopted from [6]. The computational domain of the study area was set to have a grid size of 6 m x 6 m. We have some limitations in this study. The numerical models used in this study did not simulate sediment transport. In addition, this study also did not consider debris of the collapse buildings. The trees were consider to sustain the tsunami wave. We placed observation points and cross sections to observe the hydrodynamics aspects of the tsunami waves.

2. Study Area

The Ulee Lheue Bay was chosen as the study area in this research. The area was severely damaged by the 2004 Indian Ocean tsunami. It is located on the western coast of Banda Aceh, the capital city of Aceh Province. The Ulee Lheue Bay is dominated by two types of coastal morphology. At the west part, the coastal has one headland named as Ujong Pancu. Meanwhile, at the eastern part, the area is relatively flat. According to pre-tsunami satellite imagery (IKONOS 2003), the land cover of Ulee Lheue Bay was dominated by fishponds (tambak). Beside the fishponds, this area had also beach area, forest area, settlement, and vegetation area. Before the 2004 tsunami, no hard structures for coastal protection along the coastline along this bay. The computational area of Ulee Lheue Bay ranges from 5.22°E to 5.579°E and from 95.225°N to 95.280°N. The study area is shown in Figure 1.



Figure 1. The map of Ulee Lheue Bay. The study area is marked by the red rectangle

3. Methods

Numerical simulations were performed using Cornell Multi-grid Coupled Tsunami Model (COMCOT). COMCOT model is used to simulate tsunami generation and propagation. Meanwhile, for tsunami inundation and observation of tsunami hydrodynamics, Delft3D model is used. Both models were connected at an open boundary (north boundary) using time series data of tsunami water level produced in COMCOT simulation. The methodological approach is shown in Figure 2.

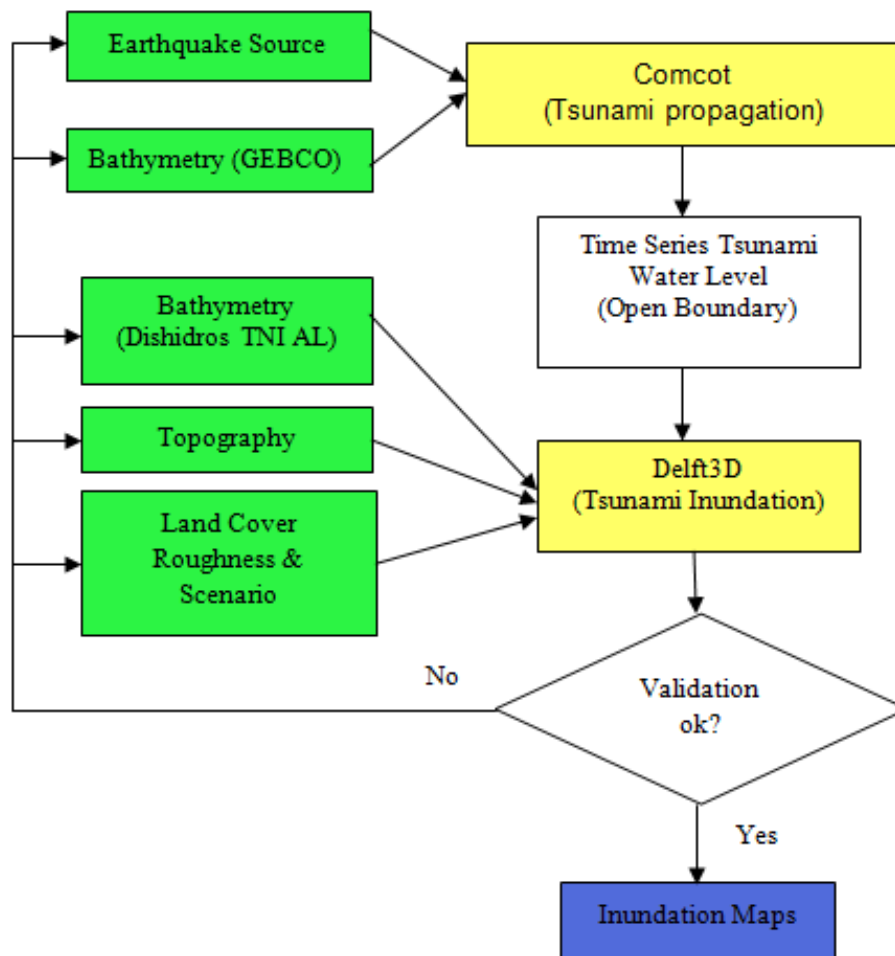


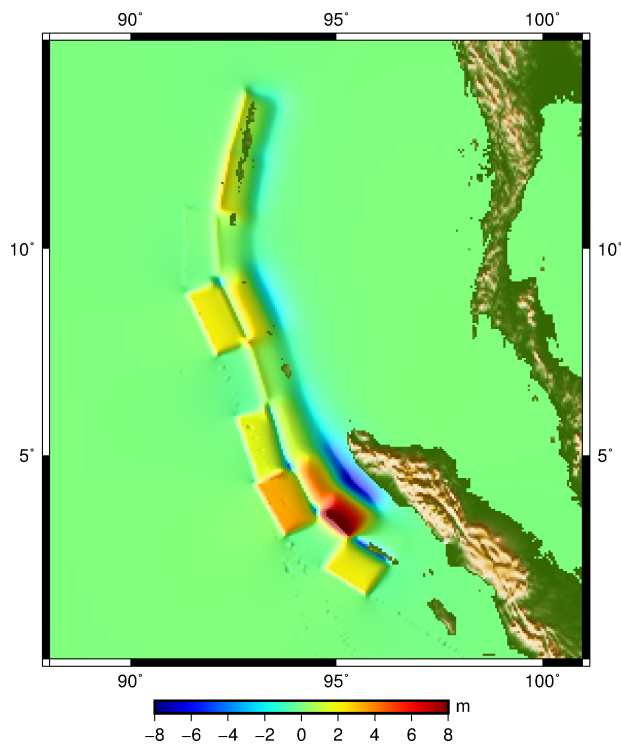
Figure 2. Methodological approach of the numerical model in this study

3.1 Earthquake source mechanisms and tsunami generation

The COMCOT model requires several data input to simulate tsunami generation. The data are bathymetry data and the parameter of the 9.1 Mw earthquake that triggered the 2004 Indian Ocean Tsunami. A list of mechanisms of the 2004 earthquake (see Table 1) were adopted from [8] and [10] have validated this model. The initial sea surface elevation map according to the source mechanisms model used in this study is shown in Figure 3.

Table 1. Multi-fault Scenario of the earthquake parameter in the 2004 tsunami event [8]

	<i>Fault segmen</i>	Coordinat		Parameter <i>Fault</i>			<i>Depth</i> (km)	<i>Dis</i> (m)	<i>Width W</i> (km)	<i>Length L</i> (km)
		<i>Long (°)</i>	<i>Lat (°)</i>	<i>Strike</i>	<i>Dip</i>	<i>Slip</i>				
9.1 Mw	1	98.845	2.671	301.8	13.22	90	10.1	5	113.728	137.154
	1	95.21	1.915	301.8	5.2	90	0.1	4	110.273	137.211
	2	94.964	3.312	309.14	13.23	90	10	16	113.624	109.662
	2	94.3	2.583	309.5	5.21	90	0.1	15	110.137	123.126
	3	94.183	4.206	328.16	13.48	90	10	5	111.504	125.25
	3	93.4	3.667	329.9	5.4	90	0.1	5	106.331	158.965
	4	93.582	5.473	336.16	14.48	130	10	14	103.985	182.4
	4	92.85	5.133	341.05	6.34	130	0.1	16	90.568	183.497
	5	93.084	7.051	342.91	14.88	130	10	5	101.266	163.41
	5	92.35	6.75	341.39	6.42	130	0.1	5	89.367	172.928
	6	92.524	8.416	334.56	14.83	130	10	15	101.569	176.108
	6	91.733	8.1667	334.66	6.14	130	0.1	16	93.561	181.21
	7	92.089	10.085	357.33	15.25	90	10	4	98.863	167.488
	7	91.312	10.075	0.77	6.5	90	0.1	5	88.3	204.321
	8	92.259	11.637	10.71	15.71	90	10	14	96.999	156.887
	8	91.562	11.75	12.08	7.12	90	0.1	16	80.698	166.563
	9	92.602	13.067	15.94	16.36	90	10	6	92.323	167.403
	9	91.988	13.25	17.23	7.79	90	0.1	16	73.763	172.847

**Figure 3.** The map of the initial surface elevation derived from multi fault model by [8]

3.2 Numerical simulation of tsunami propagation

The nonlinear Shallow Water Equations (SWE) in COMCOT are given by

$$\frac{\partial \eta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{gn^2}{h^{4/3}} u \sqrt{u^2 + v^2} = -g \frac{\partial \eta}{\partial x} \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{gn^2}{h^{4/3}} v \sqrt{u^2 + v^2} = -g \frac{\partial \eta}{\partial y} \quad (3)$$

Where η = surface elevation (m); h = the total water depth (m); u dan v = the depth average velocities in the x dan y directions, respectively (m/s); ρ = the water density (kg/m^3); g = the gravitational acceleration (m/s^2); n = the Manning's coefficient for bottom roughness.

In this study, COMCOT model was applied to five simulation layers as given in Figure 4. To compute the wave propagation for the first four layer, the linear shallow water equation and the spherical coordinate system were used. The bathymetry data for layers 1-4 were generated from the GEBCO data. The layer 5 that covered only the Ulee Lheue Bay used nonlinear shallow water equation and it was solved in a cartesian coordinate system. For the nearshore zone (Layer 5), the bathymetry data were digitized from DISHIDROS of the Indonesian Navy. The roughness coefficient in COMCOT simulation was set to $n = 0.02$ for the whole model domain simulation. In Layer 5, which is the focus of this study, the land cover roughness coefficients before tsunami were transferred into Delft3D model as Manning coefficients. The grid size of Layer 5 Delft3D model was set to 6 m x 6 m. For evaluating the coastal forest effect, we used two scenarios with coastal forest widths of 50 m and 100 m for scenario 1 and scenario 2, respectively. The details of the five layer simulations used in this study are summarized in Table 1.

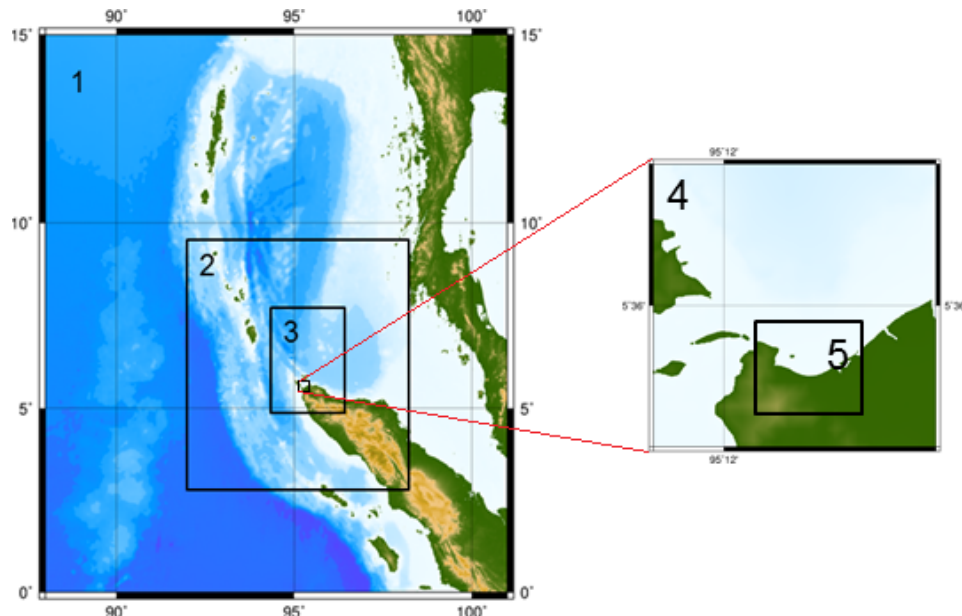


Figure 4. Simulation layer for COMCOT model

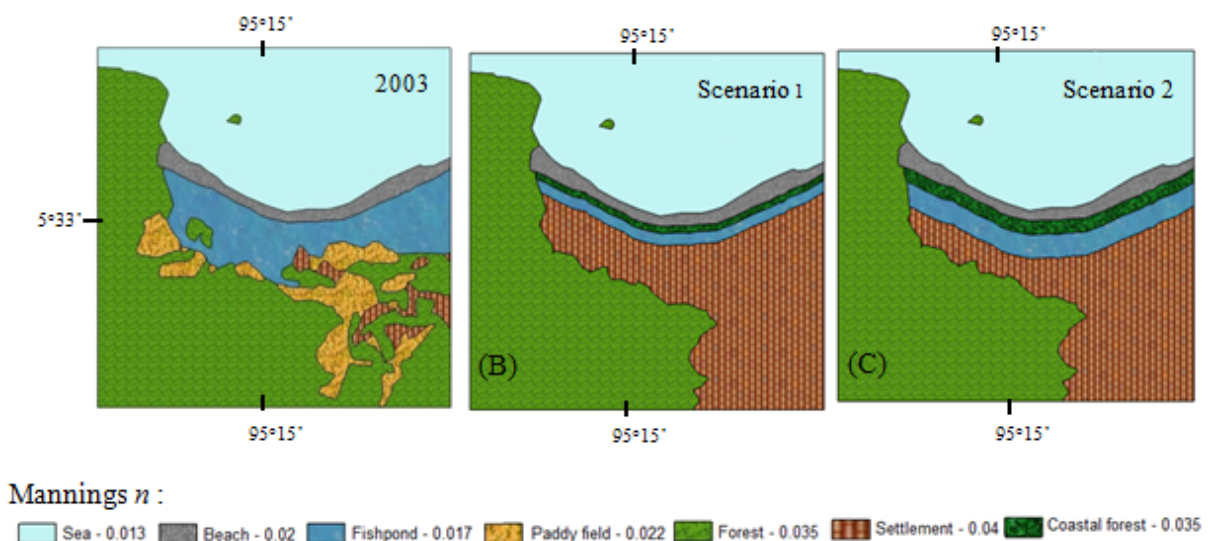
Table 1. Information on the setup of the five layer for COMCOT simulations

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Grid size (m)	1 min = 1851 m	0.5 min = 928 m	0.167 min = 309.33 m	0.056 min = 103.11 m	0.014 min = 25.78 m
Number of grids	nx = 777 ny = 898	nx = 716 ny = 596	nx = 537 ny = 519	nx = 213 ny = 210	nx = 184 ny = 188
Time step (sec)	1	1	1	1	1
Coordinate System	Spherical	Spherical	Spherical	Spherical	Cartesian
SWE	Linear	Linear	Linear	Linear	Nonlinear

3.3 Land cover roughness

In this study, land cover roughness was interpreted using Manning's roughness coefficient (n), which variation of land cover classification. The detailed maps of land cover on the innermost layer before tsunami digitize using Quantum GIS from IKONOS satellite imagery captured in January 2003. The Ulee Lheue Bay's land cover (before the tsunami) has classified into the beach, fishpond, vegetations area, settlements, paddy field, and forest. For each area, the Manning coefficient was adopted from [6]. The land cover classification around the Ulee Lheue Bay before tsunami are shown in Figure 5 (a). The smallest roughness value was specified for the sea ($n = 0.013$). Meanwhile, the smallest roughness value on land was specified for the fishpond area ($n = 0.017$). The value roughness ($n = 0.04$) is a higher roughness in this study that specified for the settlement area.

The land cover scenarios in the simulation were used to investigate the role of coastal forest on reducing tsunami wave impacts. See Figure 5 (b) and Figure 5 (c) for more details. For scenario 1, the coastal forest width is 50 m and fishpond area was set at the same width. For scenario 2, we set 100 m width for coastal forest and 100 m for fishpond area. Simulation of tsunami inundation with various Manning coefficients were performed using Delft3D model simulation. Coastal forest is assumed to be able to reduce tsunami impact. Therefore, in the simulations, we focused the observation of the results in coastal forest area.

**Figure 5.** Roughness maps on land cover in Ulee Lheue Bay (a) 2003, (b) Coastal forest 50 m width and (c) Coastal forest 100 m width

4. Results

The numerical simulation results were analyzed to evaluate the land cover influence on the tsunami inundation area. The results are presented in the spreading of maximum tsunami inundation for three types of land cover, maximum water elevation, and flow velocities.

4.1 Influence of land cover roughness on tsunami inundation

Based on the land cover condition before the tsunami, our simulation shows that the tsunami waves inundated all of the flat area in the Ulee Lheue Bay. Only at the mountain side, tsunami waves were halted (the mountain side is indicated in dark blue in Figure 6). The steeper slope of the foothill stops tsunami propagation for inundating farther inland. The results were found similar at two models scenarios of land cover. For both scenarios (Figures 6 (c) and 6 (d)), we found a minor change in term of inundation area. The results were indicated by the small difference of color scale at the southern part of inundation limit of simulation area. For more detail of the tsunami maximum water level, the results were presented at observation points A and B. Points A and B are located in front of the mangrove area. The tsunami maximum water levels at observation points A and B are presented in Figure 7. There is no significant difference in maximum water level between the simulation using land cover condition in 2003 and with scenarios using two coastal forest widths.

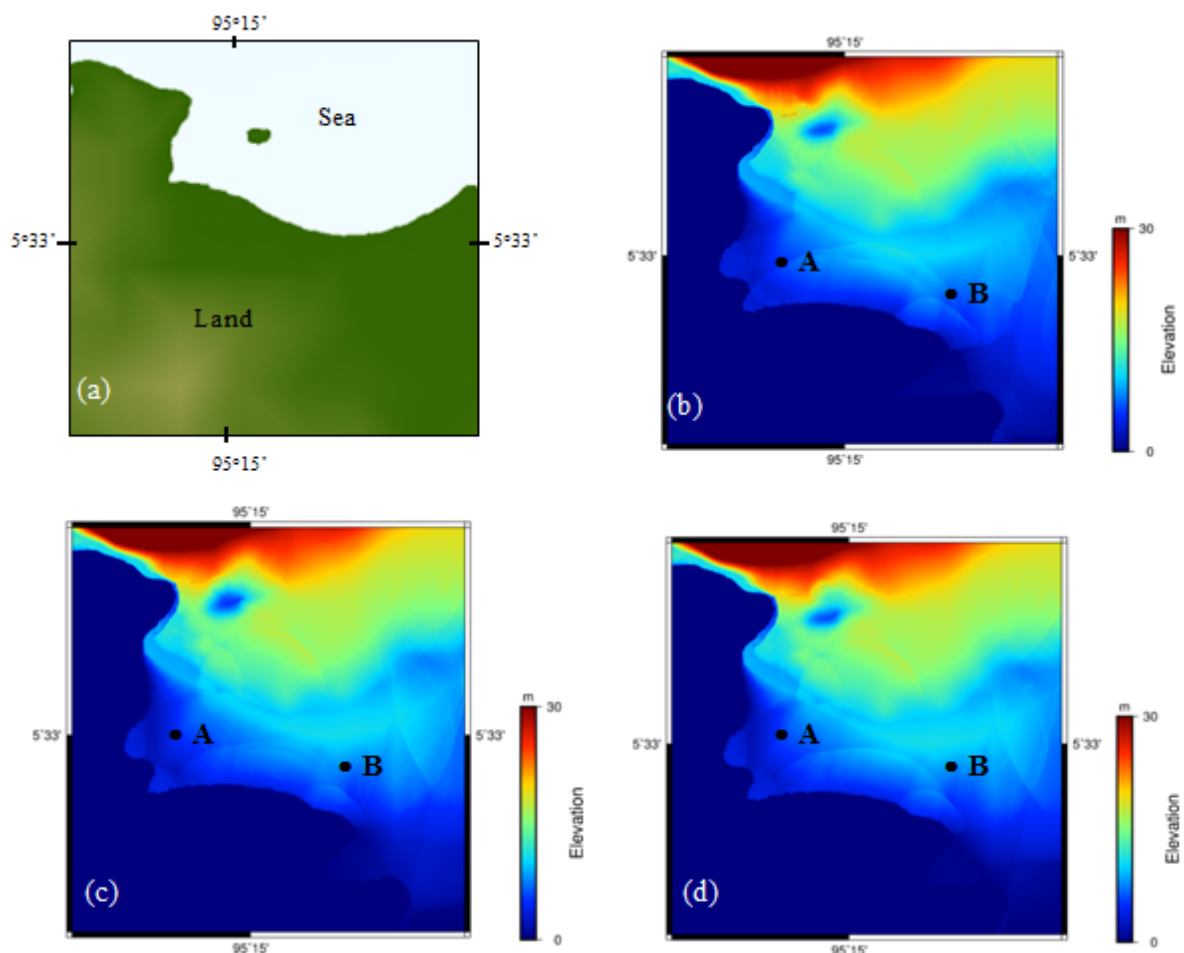


Figure 6. Maps of maximum tsunami inundation (b) Using land cover condition in 2003, (c) Coastal forest width 50 m and (d) Coastal forest width 100 m. Figure 6 (a) show the land boundary in simulation area.

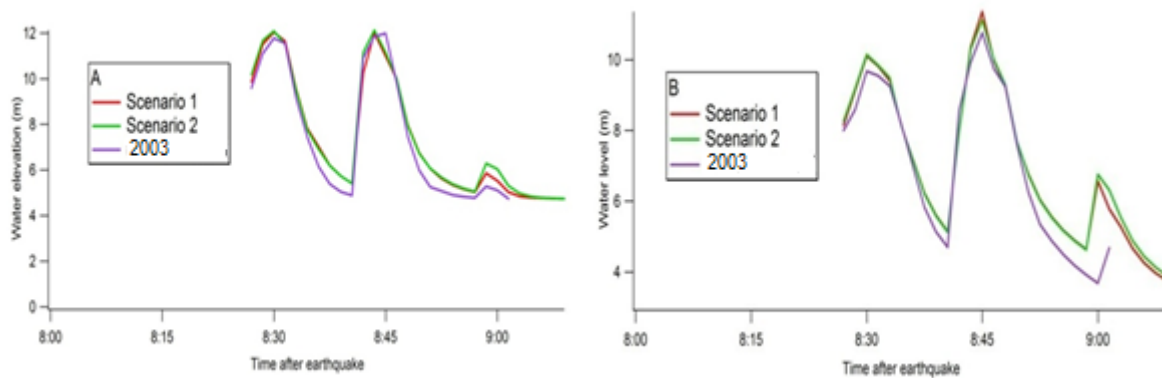


Figure 7. Differences in maximum tsunami water level

4.2 Influence of land cover roughness on tsunami velocity

On the contrary, the comparison of the velocity maximum shows more significant differences. The comparison results are shown in Figure 8. Based on observation points A and B, the purple solid line indicates the maximum tsunami velocity found in the simulation using land cover types/condition 2003 is larger than the velocity results in simulations that considered coastal forest. The first wave with the existing land cover hit the Ulee Lheue Bay with 5 m/s of velocity. On the other hand, the velocity decreased to 3.1 m/s in coastal forest with the width of 100 m and decreased to 3.0 m/s in coastal forest with the width of 50 m. The results show the velocity of the tsunami waves can be reduced approximately 40 % compared to the existing land cover in the study site.

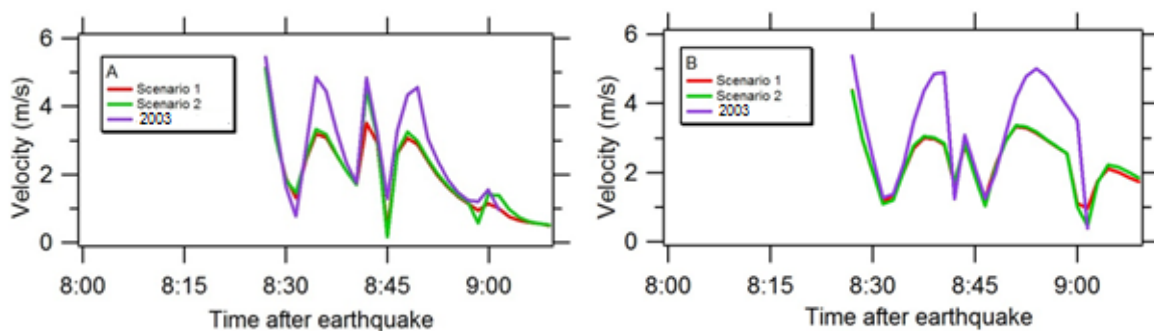


Figure 8. Differences in maximum tsunami velocity

5. Discussion

In this paper, the Manning coefficient is a sensitive parameter to response the velocity of the tsunami wave. Figure 9 presents the maximum velocity in a north-south direction for profile 3. The solid line represents the simulation across the coastline from the offshore until inundation limit. The coastal forest is located about 250 m distance from the shoreline. There is 250 m width of beach area in this cross section. The purple solid line represents the actual maximum velocity of the tsunami wave. The maximum velocity is increased with a rather consistent trend, started around the coastline until the limit of inundation. About 500 m to the land ward area, the maximum velocity in both of scenarios with coastal forest decreased with a steeper slope than the simulation results based on the land cover condition in 2003. The result shows that tsunami waves velocity decreased after being reduced by coastal forest. The 50 m width and 100 m width of coastal forests have a similar pattern of the velocity

cross-profile. The coastal slope also influences to decrease of the tsunami waves velocity. These simulations gave a similar results to a study conducted in Phang Nga and Phuket, Thailand [4].

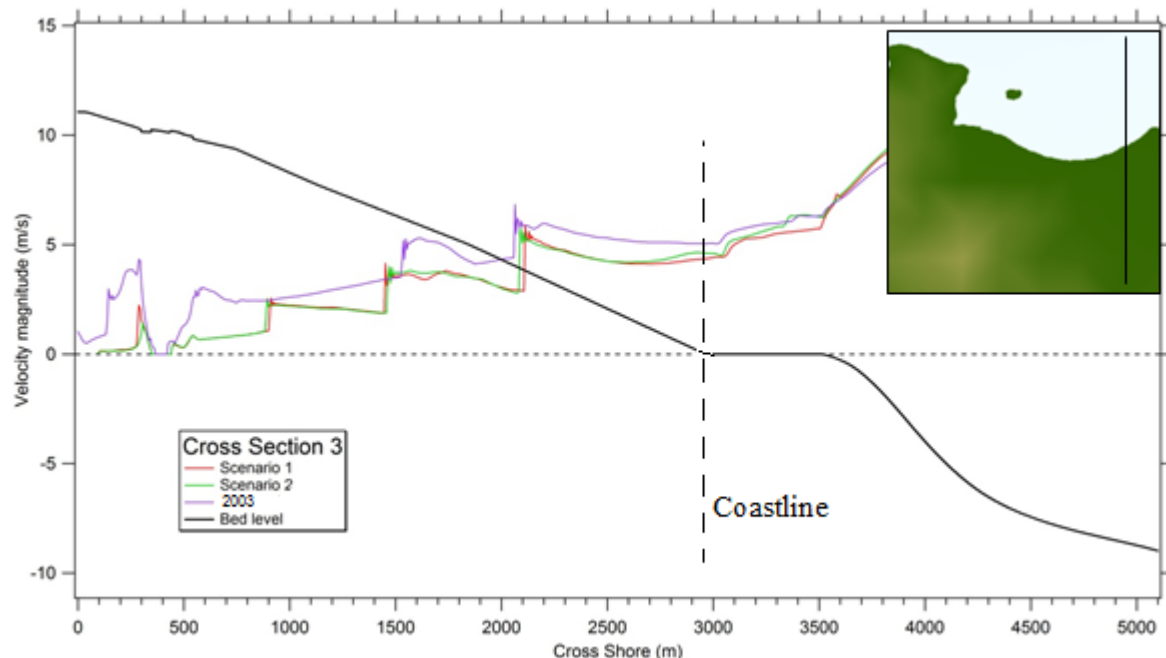


Figure 9. Maximum tsunami velocities in north-south direction for cross section 3

6. Conclusion

This paper report the numerical simulation results to investigate the role of coastal forest to reduce tsunami waves energy, in term of tsunami inundation area, the tsunami wave heights, and the wave velocity. The role of coastal forest to reduce the tsunami inundation was minor. It was shown by small differences in the area of tsunami inundation using a number of variations of coastal forest widths. However, a significant difference was seen in term of the velocity of the tsunami waves. With the land cover change to the coastal forest, the velocity of the tsunami waves can be reduced to almost 40% compared to the existing land cover found in the study site. The reducing velocity will reduce adverse impacts of future/potential tsunamis in this area. Although the topography is the most critical factor to influence the tsunami inundation pattern, the land cover roughness also needs to be considered.

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