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Reconstruction of the 2004 Tsunami Inundation Map in Banda Aceh Through Numerical Model and Its Validation with Post-Tsunami Survey Data

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Abstract. The National Oceanic and Atmospheric Administration (NOAA) recorded the 2004 tsunami heights in the Indian Ocean using the DART buoy tool and survey field data in the land side of Banda Aceh. Furthermore, 85 tsunami poles around Banda Aceh and Aceh Besar were used to mark the tsunami flow depth. The flow depth of the tsunami data recorded plays an important role in fostering our understanding of the physical tsunami wave generation and inundation using tsunami modeling. This study is aimed at comparing the results of the tsunami flow depth modeling in Banda Aceh with some measurement data from NOAA and Tsunami Poles. The tsunami modeling process was applied using the Cornell Multi-Grid Coupled Tsunami Model (COMCOT) computational program. We used 6 nested grids and the innermost layer covering the Banda Aceh region. The Layer 6 used for the variable Manning roughness coefficient represents the surface land use before the tsunami. We put 139 and 67 observation points on land to observe tsunami flow depth data according to NOAA and Tsunami pole coordinates, respectively. The result shows that NOAA data gave poor agreement with numerical simulations. A better result was obtained when using tsunami poles. We recommend increasing the use of the tsunami poles data as they were produced with a rigorous validation process for the 2004 tsunami.

Keywords: Tsunami Numerical Simulation; Flow Depth; Wave Height; Validation

1. Introduction

A tsunami inundation map was prepared to assist cities and countries in identifying their vulnerabilities to tsunamis. Banda Aceh City was one of the worst impacted areas due to the 2004 Indian Ocean Tsunami. As the most populous city in Aceh Province, city planning based on disaster mitigation is important in this area. Numerical simulations are the most flexible method in generating inundations of the reconstruction process and in estimating future forecasts. This methodology would be valid if the numerical models could be validated using actual data. Numerical models may produce unreliable estimates if initial data used as an inputs in computational tools is unrealistic. This error in fact, would further influence policy makers to commit mistakes in providing decisions in disaster mitigation, and could undoubtedly lead to panic in the community.



The National Oceanic and Atmospheric Administration (NOAA) recorded the 2004 tsunami heights in the Indian Ocean using the DART (Deep-ocean Assessment and Reporting of Tsunami) buoy tool and field survey data measuring tsunami heights in Banda Aceh. Furthermore, 85 tsunami poles around Banda Aceh and Aceh Besar were used to mark the tsunami flow depth [1]. 67 of them were located in Banda Aceh [2]. The post-survey data of the tsunami wave heights plays an important role in fostering our understanding of the physical tsunami wave generation and propagation using tsunami modeling. Research conducted by [3] used data recorded in the DART buoys to verify the tsunami modeling data in the deep ocean, as well as to generate Estimated Times of Arrival (ETA) in several tsunami potential cities in the Aceh Province. Their tsunami modeling results show realistic findings with actual events [3]. When the tsunami is run-up on the mainland, instead the process becomes more complicated. The tsunami inundation phase is a highly nonlinear process [4]. Forecasting tsunami inundation requires high-resolution bathymetry and topographic data, and validation with observed data. In the post-tsunami field survey, the flow depth and wave height was the method applied to measure the tsunami height. The flow depth is the height of the water from the ground to the tsunami water level, and the wave height is the height of water from the mean sea level to the height of the tsunami surface. Tsunami water level on land is indicated by watermarks on the walls and debris on the trees [5].

All of the tsunami processes begins from tsunami generation, propagation and inundation, almost completely simulated by the COMCOT model [6]. However, to evaluate the accuracy of the simulation model, the data validation test is needed. The objective of this study is not to validate the COMCOT model performance, which has been systematically validated with analytical solution in many tsunami cases [7]. This study just aims at evaluating the tsunami height in Banda Aceh. The validation method was adopted from the Aida function [8]. The modeled tsunami height and the observed tsunami height were compared to assess the similarities and the differences between them. In 2014, [7] and [9] validated the modeled tsunami height of the COMCOT model on the 2011 Tohoku Tsunami, and also validated the flow depth of the 2009 Samoan tsunami. They used the Aida function in order to validate the simulation result.

2. Study Area

A few days after the 2004 tsunami, a number of researchers conducted a field survey in Banda Aceh. Tsunami memorial Pole's (tsunami pole) is a tsunami monument that records tsunami flow depth on land, which was measured from the ground based on eyewitnessing. Moreover, the NOAA research team also conducted a survey that observed the tsunami height with measurements of tsunami wave height. The locations of the survey were scattered over the inundation area until the boundaries of the inundation (figure 1). Based on the satellites from Google Earth, the distance of the tsunami inundation range was computed to be 3.40 km.

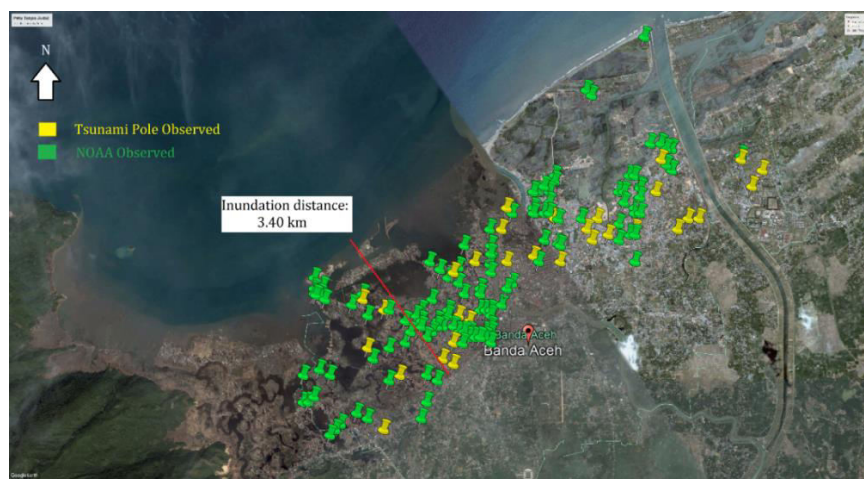


Figure 1. The distribution of post-tsunami survey location in Banda Aceh

3. Method

3.1 Numerical Simulation COMCOT

The tsunami modeling process was run using the Cornell Multi-Grid Coupled Tsunami Model (COMCOT) computational program. Six layers of grid resolution were used, and the innermost layer (Layer 6) covered the Banda Aceh region. The thrust fault event on the larger earthquake offshore Sumatra on 26 December 2004 was adopted from Koshimura [10]. Bathymetry data from Layer 1 to Layer 4 used GEBCO data with a 1-minute resolution for the outer layer. Details of topographic data at Layers 5 and Layer 6 were obtained from JICA's measurements. Layer 6 was the smallest grid with the grid cell size of 11.5 m x 11.5 m, and was run with a 1.0 second time step. The computational domain Layer 6 show in figure 2.

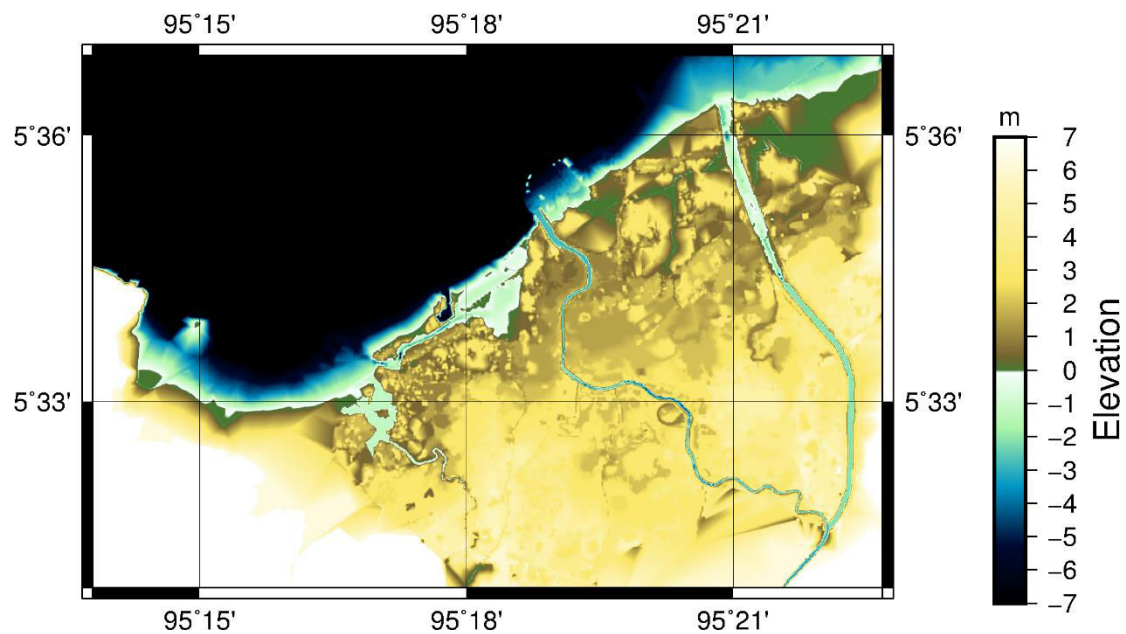


Figure 2. Banda Aceh in computational domain simulation (Layer 6). The highest land elevation is 7.0 m. Around the shore area, the topography elevation less than 3.0 m and cover half of the land side of Banda Aceh

The calculation of the tsunami waves from the open ocean was performed using the shallow water equation (SWE). The SWE's equation was applied from Layer 1 to Layer 5. Meanwhile, for the calculation of the inundation process at Layer 6, the nonlinear shallow water equation including the bottom friction effect was applied. The bottom friction of the Banda Aceh region represents the surface land use before the tsunami with Manning Roughness classification as mentioned in table 1. All of the level Layers were implemented in Spherical Coordinates.

Table 1. Manning Coefficients based on land cover in Banda Aceh before the Tsunami base on [11]

Land Use	Manning's Roughness Coefficient (n)
Coastal Vegetation	0.035
Fish Ponds	0.017
Building	0.04
Sea	0.013
Soil	0.02

3.2 Validation and Verification Flow Depth

The tsunami flow depth of the simulation results was compared with the results of the NOAA and Tsunami Pole surveys to evaluate the performance of the inundation models. There were 139 survey locations where to observe tsunami heights with NOAA data, and 67 points for Tsunami Pole data. Measurements from NOAA were based on wave height and tsunami poles were based on flow depth. The result of the COMCOT simulation is a tsunami flow depth. The illustration in figure 3 clearly delineates the definition of flow depth and wave height.

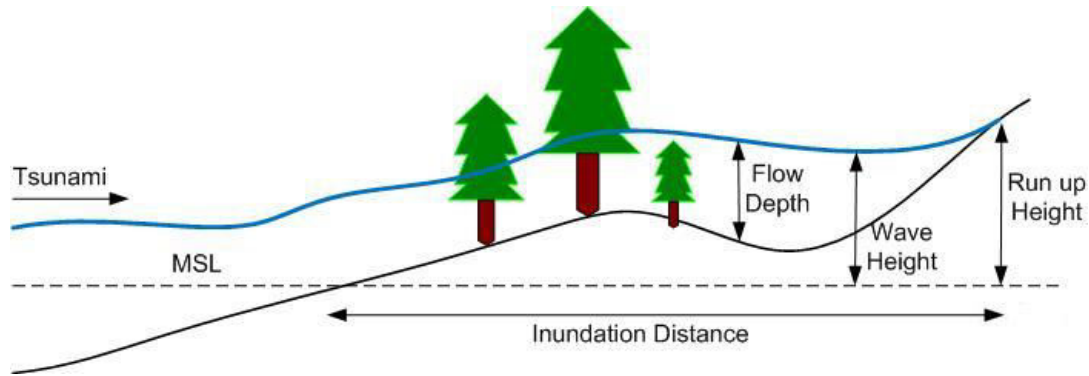


Figure 3. A diagram illustrating some terms used for tsunami measurement modified from [12]

The Aida function [8] was used as a formula to see the agreement between the simulated tsunami flow depth and the observed tsunami flow depth. The accuracy of the simulation results was calculated by using the geometric mean ratio K of the observed data (H_{obs}) and simulation data (H_{sim}), as well as the standard deviation of k .

At the survey location i , the ratio of the tsunami flow depth observed (H_{obs}) to the tsunami flow depth simulated is represented by K_i

$$K_i = \frac{H_{obs-i}}{H_{sim-i}}, \quad (1)$$

For n being a total number of observation points, geometric average value of K for all ratios is defined by the following equation.

$$\log K = \frac{1}{n} \sum_{i=1}^n \log K_i \quad (2)$$

If $K > 1$, its means that the simulation data is underestimated from the observation. However, if $K < 1$, the simulation is overestimated from the observation data. The simulation results match better with the observed data if $K = 1$. Takeuchi [13] suggests a range of values that indicates the model is a ‘good agreement’ if $0.8 \leq K \leq 1.2$ and the value of $k \leq 1.60$. The equation of the standart deviation of k as follows,

$$\log \kappa = \sqrt{\frac{1}{n} \sum_{i=1}^n (\log K_i)^2 - (\log K)^2} \quad (3)$$

4. Results and Discussion

The comparison of simulation models with measurement data is the focus of this study. The 2004 tsunami flow depth simulation with points of survey location can be seen in figure 4. The inundation map results show a pattern that is closer to the post-tsunami survey boundary location with tsunami inundation limits. An average inundation distance of 3.5 km approaches the pattern that was recorded by the Google Earth satellite. This inundation occurs approximately at the ground elevation smaller than 3.0 m or about 70% of the area Banda Aceh. Tsunami inundation from COMCOT simulation results is the maximum flow depth value.

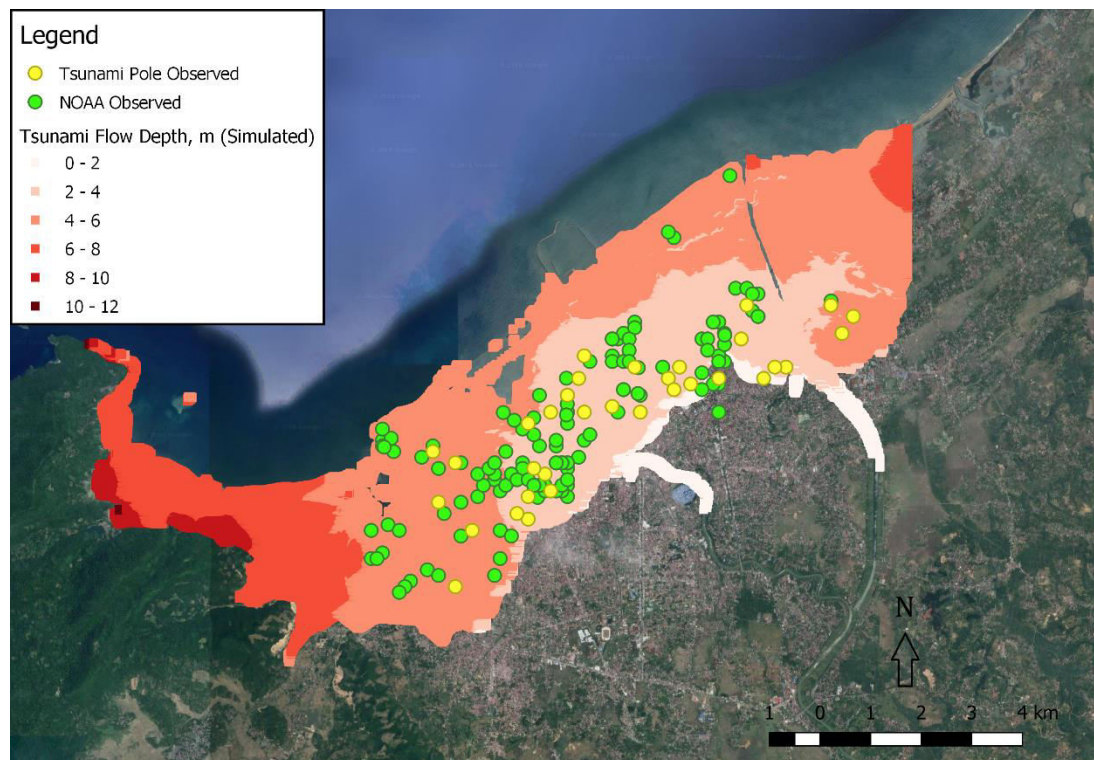


Figure 4. The 2004 tsunami flow depth simulation in Banda Aceh with several survey location by NOAA and Tsunami Pole

The simulation results were then compared with the NOAA and Tsunami Pole measurements. NOAA observed the base on wave height, and tsunami pole recorded the flow depth. NOAA measurement data was converted to flow depth data by reducing the topographic elevation value in the survey location. Table 2 show the Aida validation test for validation flow depth. The results explain that K and k values for NOAA data are outside the range value, indicating *poor agreement*. However, the Tsunami Pole data shows instead *good agreement*, with K and k values closer to the threshold value.

Table 2. K and k value for validation flow depth

Model Results	Aida parameters	
	K	k
NOAA Data ($n= 139$)	1.44	1.86
Tsunami Pole data ($n= 67$)	0.78	1.56

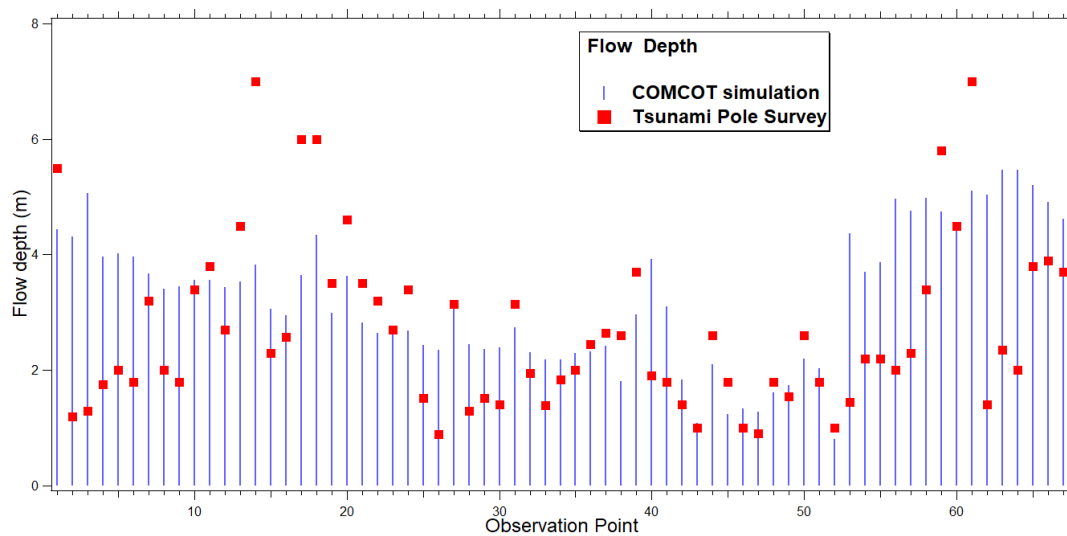


Figure 5. Tsunami flow depth compare by simulation and tsunami pole recorded

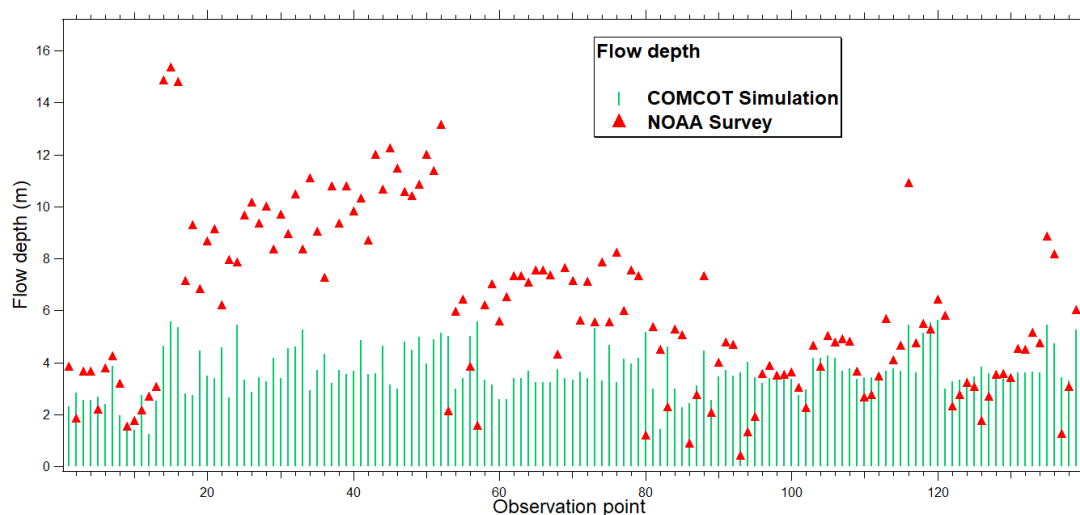


Figure 6. Tsunami flow depth compare by simulation and NOAA survey

Although some point locations were still overestimated and underestimated compared with the observed ones, the tsunami flow depth model comes much closer to the Tsunami Pole one (figure 5). Conversely, with NOAA most of the flow depth simulation values were underestimated compared to the observed ones (figure 6). This is likely due to the fact that the topographic data that interpolated into the 11.5 x 11.5 m grid size was not enough to represent the real elevation when surveyed. The pattern of the flow depth simulation can be observed in the two Figures above, showing quite similar patterns. The value of each point is in the range between 2.0 m and 6.0 m. The data from each point varies greatly compared with the observed one. There is a possibility that the splashing water cannot be modeled properly with the grid size in the model. Even though the determination of the flow depth is measured at the highest limit of water, higher traces caused by splash water can be found in the observed data.

5. Conclusion

High-resolution topographic data and numerical validation results with observed data will produce accurate results in inundation maps. NOAA data gave poor agreement with numerical simulations. A better result was obtained when we using tsunami poles. We recommend to increase the use of the

tsunami poles data as they were produced with a rigorous process of eyewitness validation after the 2004 tsunami. Validation model is a continuous process. Even if the model has already been validated, additional testing is also required to constantly bring new knowledge to future studies.

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