Estimating Impacts of Tsunami on Buildings around Ambon Bay of Indonesia

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Abstract. Ambon is a city situated inside a long bay in eastern part of Indonesia. The city has been stricken by a number of tsunamis in the past. The last tsunami event was generated by a submarine landslide inside the bay that hit two villages in the city in 1950. Despite the long story of tsunamis inside the Ambon city, no study has been conducted to estimate the impacts of future tsunamis on the growing coastal area of Ambon. This study was aimed at assessing the building vulnerability in Ambon due to projected impacts of future tsunamis. A numerical simulation was performed to generate tsunami inundation areas in the city using Cornell Multi Grid Coupled Tsunami Model (COMCOT) based on maximum fault area in the segment. A series of field works to classify the building types in the city were performed in May 2023 on around 70,000 units of buildings along the bay of Ambon. The classifications were done using Hazard United States (HAZUS) frameworks. Tsunami fragility curves were used to estimate the impacts of the tsunami based on flow depths obtained from the numerical simulations. Based on the surveys, this study found that buildings within 200 m from coastline of the bay could be in Damage State 4 (DS4) which is the most severe impacts of tsunamis on buildings.

1 Introduction

Tsunami is a constant threat for most coastal cities in Indonesia. However, the tsunami research for eastern part of Indonesia receives less attention than the western part of Indonesia. This contributes to lack of understanding of the characteristics of the hazards, mitigation measures, and ways to include them in the development of the cities (1,2).

Tsunami in a long bay has been recorded to generate amplification process where its runup could be higher than plain coast. There have been a number of studies done to observe or to estimate hydrodynamic process of tsunami in a bay. In recent years, the 2018 Palu bay tsunami has ignited scientific debates on the process that led to the tsunami event (3–5). The narrow, deep, and long bays could potentially amplify the tsunami waves and create more adverse impacts on the area along the bay.

Ambon is another eastern Indonesia city that is situated inside a long bay. This is similar to the condition of Palu. However, as explained earlier, the eastern city also receives less attention on tsunami mitigation compared to other areas. This has motivated this study in order to have a better understanding on potential impacts of tsunami in future.

Assessing impacts of future tsunami on buildings is a challenging topic as the research would need to combine between the hydrodynamic forces of tsunami and the vulnerability aspects of the buildings (6–8). Exact impacts of tsunami on buildings would be difficult to assess in an extensive area, such as in the case of Ambon. A more realistic approach to this would be by combining between numerical simulations and statistical analysis. This is where tsunami fragility curves could be off important tools. However, it must note that comprehensive empirical tsunami fragility curves based on buildings characteristics in Indonesia are still not available (9). One of the reasons due to lack of the studies to compile all building types and assess the impacts based on past tsunami events.

This study was aimed at assessing the building vulnerability in Ambon due to projected impacts of future tsunamis. For the area of the study, this is considered to be first study that combined the numerical simulation results and building vulnerability. It is expected the study would draw larger attention from related stakeholders on measures to mitigate impacts of tsunami for the area. Furthermore, this study will fill tsunami research gaps for eastern region of Indonesia.

2 Study Area

Ambon is an eastern Indonesia city that is situated along the bay of Ambon (see Fig. 1). The city is the largest and the capital city of Maluku Province. In 2022, Ambon has population of around 349,000 people. The city is divided into five sub-districts, namely Nusaniwe, Sirimau, Leitimur Selatan, Ambon Baguala Bay, and Ambon Bay sub-districts (*kecamatan* in Bahasa Indonesia). Four sub-districts, except for Leitimur Selatan, are located along the Ambon bay. The largest populations are reported from *Kecamatan* Ambon Baguala Bay. The most populated sub-district is *Kecamatan* Sirimau where around 42% of the city population reside here.

The morphology of the Ambon Bay is shaped with two parts, i.e. inner bay and outer bay. The two parts is divided by a narrow strait where *Merah Putih* bridge connect the north and the south parts of the bay. The inner bay has a relatively shallower depth than the outer bay. At the outer bay, the deepest part can reach to around 650 m, which is located around the bay entrance. Meanwhile in inner bay, the deepest part is about 30 m.

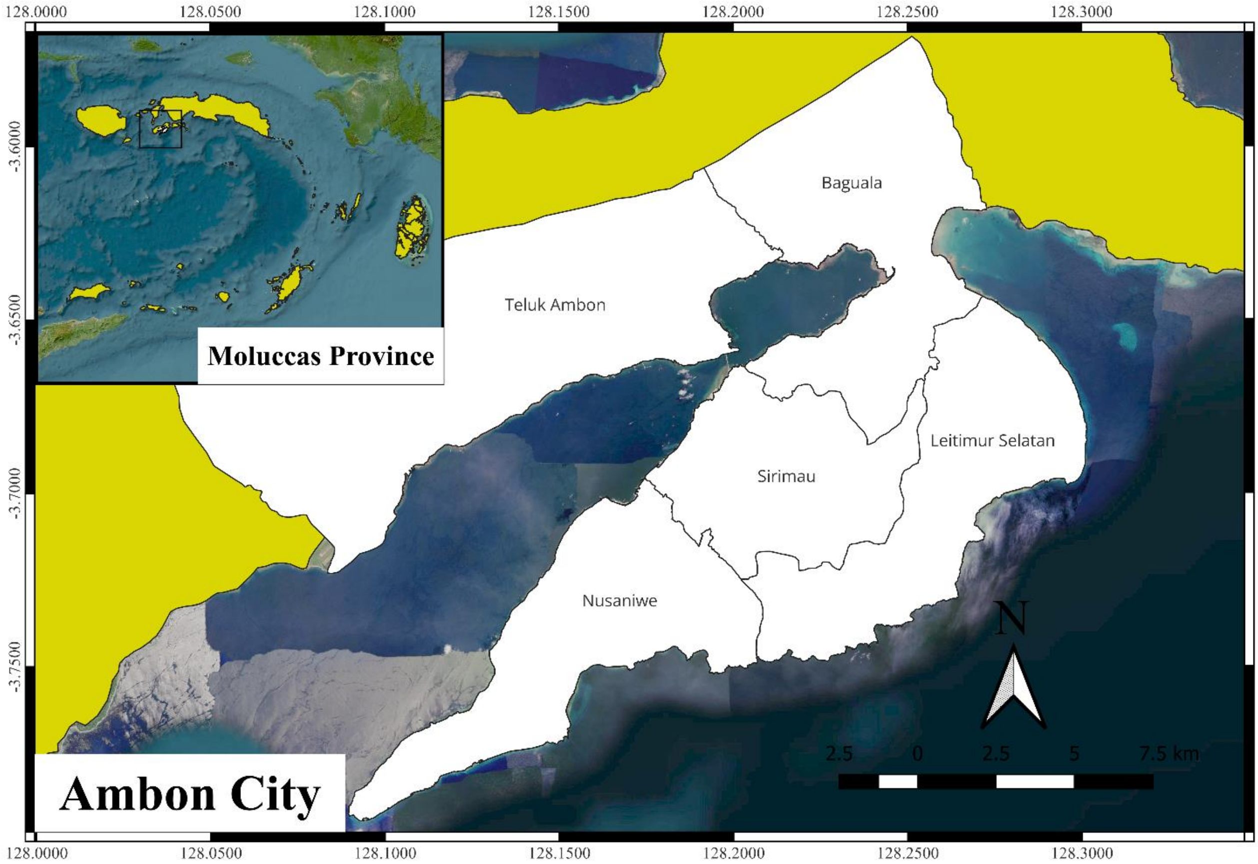

Fig. 1. The Ambon Bay. The inset map is the Maluku Island of Indonesia.

3 Methods

In assessing the potential damages due to the tsunami in Ambon Bay, this study was performed in two stages. First, a numerical simulation was conducted based on the largest predicted event from the North Maluku Segment. Second, a series of buildings were conducted to assess the buildings tsunami vulnerability around the Ambon Bay. The following sub-sections will further elucidate the methods.

3.1 The Numerical Simulation

At this stage, wave propagation simulations were performed with the Cornell Multigrid Coupled Tsunami Model (COMCOT) numerical modeling. COMCOT is a two-dimensional numerical model that uses Linear Shallow Water Equation (SWE) and Non-linear Shallow Water Equation (NSWE) based on depth-averaged velocity. Both equations are solved using the leap-frog method.

Table 1. Simulation Layers

Layer	Lon		Lat		Num. of Grid	Grid Size (m)	Ratio
	min	max	min	max			
1	124.13	135.13	-11.62	0.83	660.0 x 747	1856	1
2	126.07	130.27	-5.75	-1.61	504.0 x 497	928	2
3	127.07	129.27	-4.70	-2.61	528.0 x 513	464	2
4	127.57	128.77	-4.25	-3.11	864.0 x 820	155	3
5	127.82	128.52	-4.00	-3.36	2016.0 x 1843	39	4
6	128.00	128.32	-3.80	-3.56	2160.0 x 1728	15	2.5

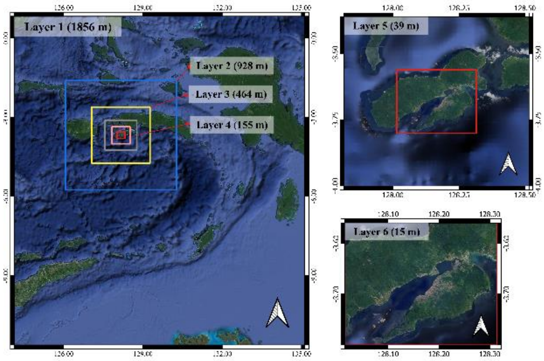

Fig. 2. The layers of the tsunami numerical simulations (overlayed on Google Earth images).

The simulation is divided into six layers in Table 1, and Fig. 2 also shows the simulation map. Layers 1-5 use the SWE equation with bathymetry data for simulation efficiency and accuracy issued by the National Bathymetry (BATNAS). While layer 6, a detailed layer, applies NSWE with DEM data obtained from the National DEM (DEMNAS). The equation in layer six is expected to represent the hydrodynamic effects in coastal areas by incorporating Manning's Roughness Coefficient (n) according to the land use type of each grid [14].

Table 2. Rupture Parameters.

Mw	Epicenter		L (km)	W (km)	Depth (km)	Strike (°)	Dip (°)	Rake (°)	Dis (m)
	Lon.	Lat.							
9.1	131.642	-4.654	100	132	10	310	40	90	16.86
	130.717	-4.055	150	132	10	294	40	90	16.86
	129.561	-3.759	120	132	10	270	40	90	16.86
	128.251	-3.854	180	132	10	268	40	90	16.86
	126.753	-3.970	150	132	10	272	40	90	16.86

This study uses a deterministic tsunami model based on the largest earthquake magnitude of 9.1 Mw with the rupture shown in Table 2. The dimensions of the rupture area deforming the seafloor along the Eurasian, Pacific, and Indo-Australian Plates are calculated using the scaling law proposed by Wells and Coppersmith [wells coppersmith]. The dip and rake parameters in this scenario were taken from the study of Pranantyo et al. based on the history of the 1950 Ambon tsunami centered in the North Banda Sea [11] [12]. This study harmonizes the rupture area scenario along the North Banda Sea subduction zone.

3.2 Building Vulnerability Assessment

To estimate damages caused by tsunami forces, a set of fragility curves were used. Reviews on the tsunami fragility curves show that the empirical formulas were characterized by mechanisms of the tsunami generation and types of buildings. Based on the reviews, the closest set of the curves were produced from the 2011 Great East Japan Earthquake and Tsunami. The empirical tsunami fragility curves were composed based on some 50,000 units of buildings damaged by the tsunami in the eastern area of Tohoku region of Japan [19], [20].

The general fragility form used in this research can be seen in Eq (1).

$$P(x) = \phi\left[\frac{ln\, x - \mu'}{\sigma}\right], \qquad (1)$$

Here, *P(x)* is probability function of the damage, ϕ is a normal distribution function, x is a hydrodynamic feature. In this research, we used tsunami flow depth as the feature. μ' is a mean value of the $\ln x$. Meanwhile, σ is a standard deviation of $\ln x$.

Table 3. HAZUS Classification

Label	Description	Information
C3-L	Concrete frame with unreinforced masonry infill walls	1-3 stories building or 20 feet high
C1-LA	Concrete moment frame	1 story or 20 feet high
C1-LB	Concrete moment frame	2 stories or 20 feet high
C1-M	Concrete moment frame	3-7 stories or 50 feet high
S1-L	Steel moment frame	1-3 stories or 24 feet high
S1-M	Steel moment frame	Over 3 stories or 60 feet high
W1-L	Wood light frame	1 story or less than 12 feet high

Table 3 shows the classification of buildings based on HAZUS. The digitized building footprint then classified and validated based on the results of a building survey in the city of Ambon.

Table 4. The level of damage and probabilistic value

Classification	Damage Condition	Probabilistic Value Range
DS0	No damage	$10\% < P(x)$
DS1	Minor Damage	$10 \leq P(x) < 35\%$
DS2	Moderate Damage	$35\% \leq P(x) < 75\%$
DS3	Major damage	$75\% \leq P(x) < 90\%$
DS4	Collapsed	$P(x) \geq 90\%$

This section discusses a study conducted by Suppasri on the likelihood of buildings getting damaged (damage state) [10]. In Table 4, the types of potential damage that buildings might experience are described. The fragility of a building is categorized into five levels based on its probability of getting damaged [13].

4 Results and Discussion

4.1 Tsunami Inundation Area

The characteristics of the Ambon Bay area tend to narrow in the inner bay. In the narrowing area, this condition leads to a significant increase in the volume of wave propagation. Fig. 3 shows the tsunami runup based on a numerical simulation with the maximum runup is ±12 m. Tsunami runup that occurred in the narrowing area of the bay. This condition shows similarities between the numerical simulation result and the 1950 tsunami that tsunami hit Negeri Galala and Hative Kecil [12].

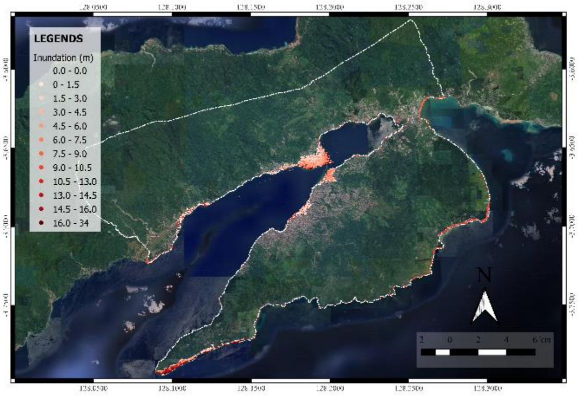

Fig. 3. Tsunami inundation based on the numerical simulation with magnitude 9,1 Mw

4.2 Buildings Distribution

Based on the results of the survey we conducted in May 2023, at least 39558 from 80188 units of building data that were successfully obtained. The data is grouped based on HAZUS in the building distribution map, as shown in Fig. 4. Ambon City has the characteristics of buildings on the coastline. It must be considered because Ambon has a history of tsunamis.

Fig 5 shows that most building in Ambon are dominated by building type C3-L (concrete frame with unreinforced masonry infill walls) in the residential areas. There are not many building with Steel Moment Frame (S1-L and S1-M) in Ambon. Only a few buildings can be seen in the downtown. The rest are warehouses. Most of that building are found in the downtown that dominated by Concrete Moment Frame (C1-LA, C1-LB, and C1-M). During the survey, it was almost invisible for wooden buildings (W1-L).

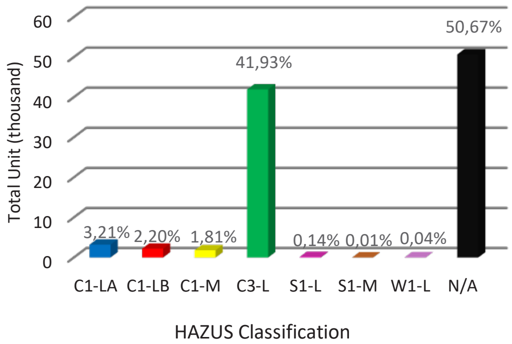

Fig. 5 Percentage number of building identified based on HAZUS.

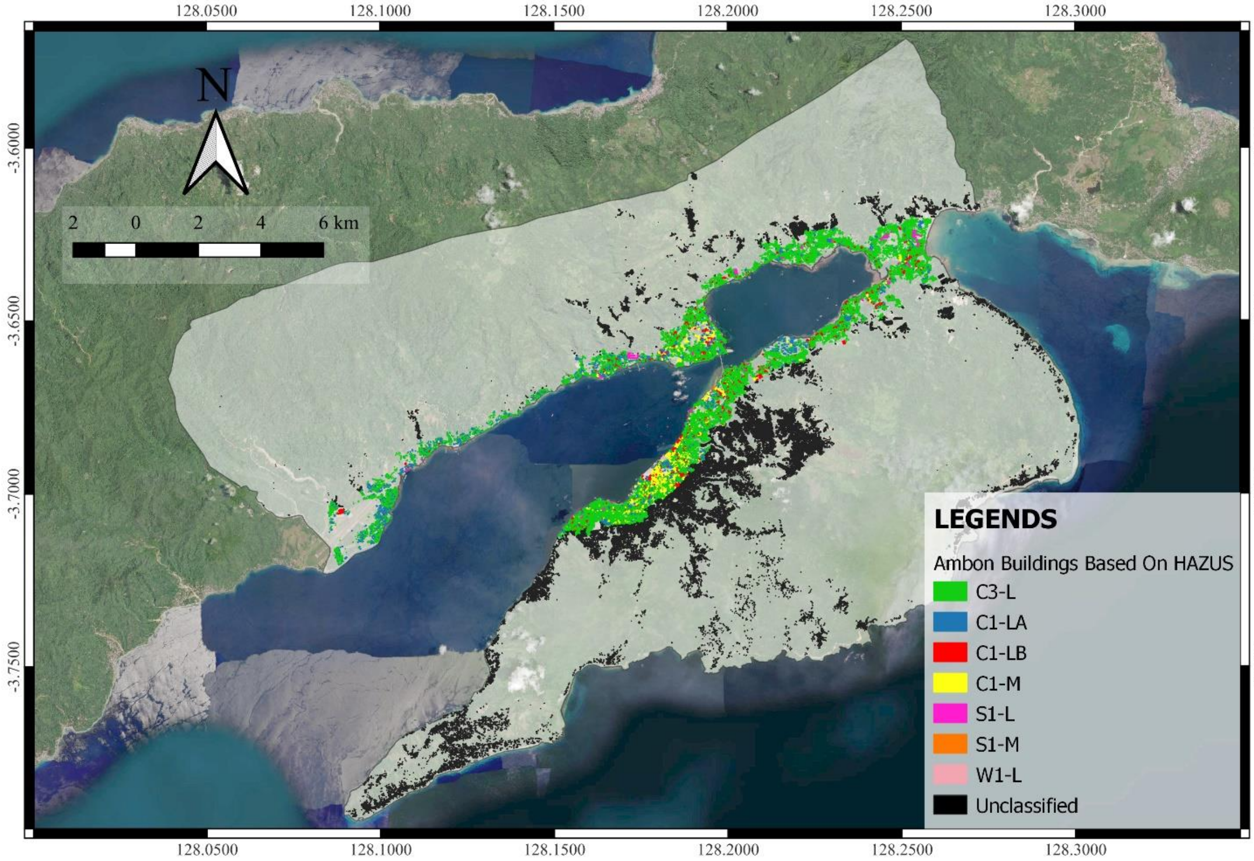

Fig. 4 Buildings Identified Based on HAZUS

4.3 Impacts on Buildings

The distribution of damage to buildings due to tsunami inundation can be seen in Fig. 6. This map shows that most of the impacted buildings are located around the narrowing of the bay. Based on tsunami inundation map, most of the damage occurred in the narrowed area.

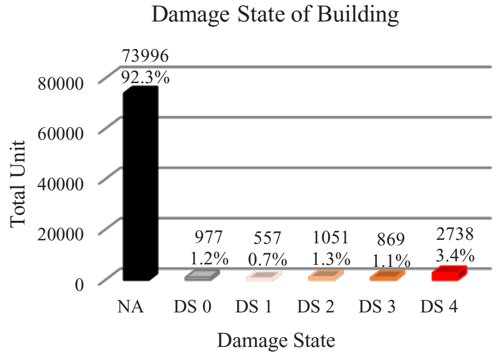

Fig. 6 Bar chart of building damages based on deterministic method.

Based on the bar chart in Fig 7, at least 7,7% building are impacted, and 92% have not. Although are significant differences, it should be noted that downtown is located on the coastline and currently experiencing an impact of 7.7%. The buildings that are affected which was dominated by not strong materials. Unfortunately, the standard used to determine the damage state is the fragility curves in Japan. This is clearly different from the characteristics of buildings in Indonesia. It is not possible to determine the fragility standard of buildings in Indonesia because it has to wait for events. Then used, fragility data with Japanese standard buildings. Nevertheless, this gives an idea of the potential disaster threat.

Fig. 7 Buildings Impact Map of Tsunami Based Tsunami 9.1 Mw

5 Conclusions

Based on the results of the survey in Ambon, the majority of buildings in residential areas are of the C3-L type, which is characterized by a concrete frame with unreinforced masonry infill walls. The impact on buildings is 7,7% generated by tsunami 9.1 Mw. However, the downtown area is situated along the coastline and is currently being impacted by 7.7%. The maps of the projected impacts on buildings in Ambon could be used as information to manage the spatial planning of the city as well as to plan tsunami evacuation procedure for the commmunity at risk in Ambon.

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