Assessing the Economic Losses Impact on Buildings Based on Tsunami Hazard in Banda Aceh, Indonesia

Muhammad Daffa Al Farizi[1,3], Syamsidik[1,2,3*], Mubarak[1,2]

[1] Civil Engineering Master Program, Civil Engineering Department, Faculty of Engineering, Universitas Syiah Kuala, Darussalam, Banda Aceh, 23111 Indonesia
[2] Civil Engineering Department, Faculty of Engineering, Universitas Syiah Kuala, Darussalam, Banda Aceh, 23111 Indonesia
[3] Tsunami and Disaster Mitigation Research Center (TDMRC), Universitas Syiah Kuala, Jl. Hamzah Fansuri No. 8, Darussalam, Banda Aceh, 23111 Indonesia
*Corresponding author: syamsidik@usk.ac.id

Abstract. Tsunami, caused by undersea seismic activity, pose a severe threat to coastal areas worldwide. Apart from the loss of human lives, these colossal waves result in substantial economic damages. Their recurrence is tied to earthquakes, thus the probabilistic occurrence of tsunami resulting from earthquakes tends to have the same potential recurrence period as the earthquake events. The devastating tsunami that struck Aceh, Indonesia, on December 26, 2004, serves as a tragic example of the economic losses caused by tsunami. The tsunami's impact on Aceh's economy was profound, requiring long-term efforts to rebuild critical infrastructure and revive economic activities. Based on the 2004 tsunami event, it was learned that tsunami occur with the same return period as earthquakes. Therefore, this study is an extension aimed at identifying the economic losses resulting from a tsunami hazard. The tsunami modeling utilizes the numerical method COMCOT with a magnitude of 9.2 Mw. To assess building damage, the fragility function equation is employed to determine the percentage of damage to structures. We simulate the losses resulting from a tsunami with a magnitude 9.2 Mw, focusing only on buildings in Banda Aceh. The buildings are classified according to the Hazard United States (HAZUS). We have found that the losses caused by tsunami disasters on buildings are significant. This makes tsunami one of the disasters with a major economic impact. This information is crucial in determining the potential losses from disasters and estimating the expected maximum financial costs.

1 Introduction

Tsunami is still one of deadliest natural events that could cause staggering losses and human casualties. The impacts of the tsunami on buildings could be recorded but still need further studies on projecting its potential losses due to the impacts. In recent years, researchers have been trying to adopt seismic vulnerability methods in projecting the economic losses due to tsunamis [1,23], [2]. However, there is still a significant gap between available data and published results of the projection [3]. Among the serious problems are lack of fragility/vulnerability curves of the assessed objects to estimate damages caused by the tsunami. Since 2010, a number of studies have been performed to produce empirical tsunami fragility curves based on events [4]–[7]. However, it is understood that characteristics of buildings in tsunami impacted areas were different to each other. Furthermore, validity of generic fragility curves that can be applied for all types of buildings is difficult to achieve. Compared to earthquakes, empirical tsunami fragility curves are far more difficult to compose as the frequency of the tsunami event is longer than earthquake in general.

Estimating economic losses due to impacts of tsunami is essential in providing a strong basis for tsunami risk reduction in an area. This includes providing strategies in disaster finance and insurance for public and private assets [8]. Conventional methods in tsunami damage and loss analysis are widely applied in Indonesia. The methods did not consider any fragility aspect of the physical damages on buildings but rather assumed them as exposed objects. By classifying them into exposed objects, later the calculation is continued to quantify the losses based on tsunami flow depths categories. Here, the classification of tsunami hazards is based on three classes, i.e., low for flow depth shallower than 1.0 m, moderate for flow depth between 1.0 and 3.0 m, and high for flow depth deeper than 3.0 m. Such a method does not clearly incorporate probability functions of the damage. Coupling hydrodynamic features of tsunamis with building fragility curves will facilitate ways to estimate the losses in probabilistic ways and time-dependent results (with return period). In the context of the impact of tsunamis on buildings in Indonesia, such studies are still rare [9]. This resulted in some policy implications, including allocating on-call budget for disaster at national and local government levels and disaster insurance premium with flat rates.

This study is aimed at applying tsunami fragility functions to estimate damages and economic losses on buildings based on an event. The impacts of the 2004 Indian Ocean tsunami on buildings in Banda Aceh was taken as the study case for the application. The study case was selected as this is the largest impact of a tsunami in Indonesia in the last century. Also, the case of Banda Aceh is relatively well documented and was studied by various researchers. These could help our research to validate and compare the research results.

The 2004 Indian Ocean tsunami (IOT) caused at least 130,000 people to die in Aceh-Nias of Indonesia [10]. In terms of buildings, areas within around 5 km

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

from the coastlines of Banda Aceh were severely damaged and buildings were swept away. The 2004 IOT was triggered by a series of earthquakes with maximum magnitude of 9.2 Mw along the Aceh-Andaman megathrust segment. The segment is located around 500 km to the northwest of Sumatra. The earthquake created a large undersea rupture area and caused a gigantic tsunami within 45 minutes after the earthquake in Banda Aceh. In the city, around 70,000 people died. Prior to the 2004 IOT, buildings in Banda Aceh were dominated by wooden frame buildings (W), confined masonry type buildings (CM) and Reinforced Concrete (RC) types. In recent years, there were rare wooden frame buildings in Banda Aceh. Mostly, the buildings are now CM types around the coastal area and RC around the Central Business District (CBD) in Banda Aceh. The CBD is located around 5 km from the coastline. This study is expected to compare the damage/losses on buildings in Banda Aceh during the 2004 IOT and recent conditions. The results are projected to be one of scientific basis for further economic losses due to impacts of tsunami in Indonesia.

2 Study Area

Banda Aceh is situated between the conjuncture of the edge of the northern part of Sumatra and the Andaman Sea (see Figure 1). A paleo tsunami study revealed that this area has been hit by at least 11 times of tsunami since 7,400 BC [11]. In recent years, a series of research have been conducted to map the potential damages due to impacts of tsunamis with various scenarios. That includes some long-term projections of impacts to some hundred years from the present. However, no studies have been conducted to map economic losses due to impacts of tsunami on the city.

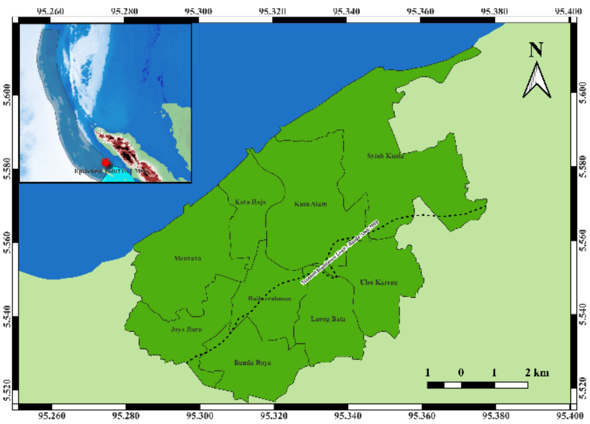

Fig. 1. The Study area. A star in the inset map shows the epicenter of 9.2 Mw earthquake taken as the source of the tsunami.

The city has a population of about 290,000 people as of 2022. Recent development of the city, about 19 years after the 2004 Indian Ocean tsunami has triggered significant changes in terms of building types and coastal area management. There is about 30% of buildings growth in the last five years in the city dominated by CM- and RC-types [9]. Massive tsunami reconstruction process between 2005 and April 2009 successfully reconstructed houses around the tsunami affected area for some ten thousand units.

3 Methods

This study employed three steps of the research; first, we performed a tsunami numerical simulation. Second, we assessed potential damages using tsunami fragility curves. Third, we quantified the economic losses due to damages on buildings in Banda Aceh.

3.1 The Numerical Simulation

The tsunami numerical simulation was performed using Cornell Multigrid Coupled Tsunami Model (COMCOT) [12]. This model has been widely used and validated since it was first introduced to tsunami researchers in 2007 [13]–[15]. The model applies two modes of linear shallow water equations, namely linear (SWE) and nonlinear shallow water equations (NSWEs). Both equations were solved using leap-frog solutions for finite difference equations.

The domain of the simulation was divided into six layers to cover from the source of the tsunami location around the Aceh-Andaman Sea until its innermost layer covering Banda Aceh (see Fig. 2). The layer 6, which is the innermost layer of the simulation, applied NSWEs. Other layers applied SWEs for the reasons of simulation efficiencies and accuracies. NSWEs are expected to represent the effects of nonlinear hydrodynamics around coastal areas. One of them was by inserting varied Manning Roughness Coefficient (n) following the land use type of each grid in the layer [16].

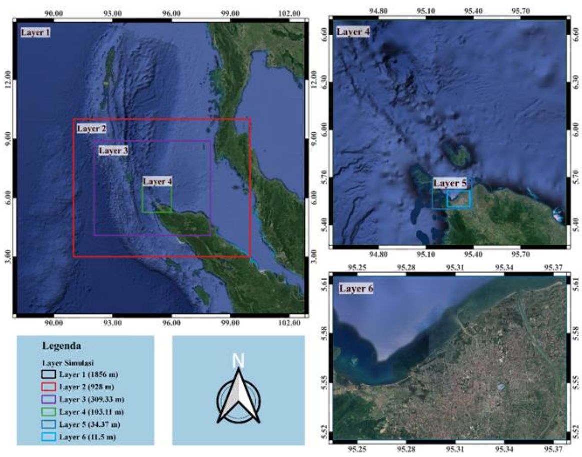

Figure 2. The layers of the tsunami numerical simulations (overlayed on Google Earth images).

An earthquake source for the simulation was taken from the 2004 IOT. There are a number of scenarios of the fault. In this study, we used a multi-fault scenario proposed by Koshimura et al. in 2009 [17]. This multi-fault scenario has been validated using tsunami flow depths measured inland of Sumatra. The fault dimension and rupture area were calculated using Wells-Coppersmith and Scaling Law Methods [18].

3.2 Tsunami Fragility Curves

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 $\ln x$.

3.3 Economic Losses

The losses due to damages caused by the tsunami were calculated using Eq. (2). This equation assumes that the ratio of the losses equal to probability of the damage *P(x)*. Later, the ratio was multiplied with the assets value of each building.

$$L_T = \sum_{i=1}^{N} P(x)_i . V_i \qquad (2)$$

Here, L_T is total losses in USD, V_i is the value of the building in USD, i is the number of the building, and N is total building counted for the losses.

4 Results and Discussion

4.1 Tsunami inundation area

The simulation of the tsunami runup based on the 9.2 Mw event gave a similar result to the 2004 Indian Ocean tsunami event. Fig. 3 shows the maximum extent of the tsunami runup based on the numerical simulation. Dash-lines show the maximum extent of the 2004 Indian Ocean tsunami digitized by TDMRC USK team.

Fig. 3 illustrates the tsunami that occurred in Banda Aceh which was simulated by Tursina et al. [21] using COMCOT numerical modeling. The tsunami that occurred based on the simulation resulted in an inundation area of 38.78 km^2 and a maximum tsunami height of about 7 meters. The seawater conditions during the simulation were MSL (Mean Sea Level-Rise) conditions.

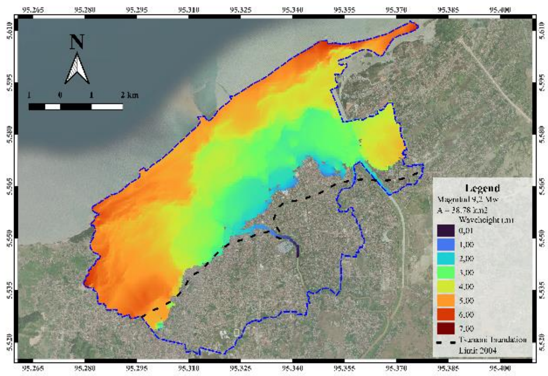

Fig. 3. Maximum tsunami runup based on the numerical simulation with magnitude 9,2 Mw

Based on the results of the tsunami numerical simulations, calculations were made to obtain a tsunami inundation area for a return period of 860 years. Fig. 4 illustrates the tsunami generated from a probabilistic tsunami hazard analysis.

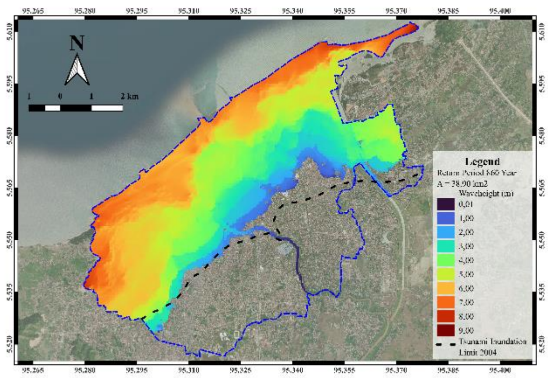

Fig. 4. Maximum tsunami runup based on the probabilistic tsunami hazard analysis for a return period of 860 years.

Fig. 4 presents the tsunami that has the same return period as the 2004 Aceh tsunami. Tsunami return period is the average time period between tsunami events that is calculated with the same or greater inundation height or tsunami intensity. The calculation of the tsunami return period uses the PTHA equation. Tsunami return periods are calculated to measure the hazard and the risk due to tsunamis in an area.

The tsunami inundation area resulting from the PTHA calculation is 38.90 km^2 with a maximum height of about 9 meters. This shows that the tsunami that occurred in Banda Aceh based on a return period of 860 years has a higher probabilistic inundation height than the tsunami caused by 9.2 Mw. This is because probabilistic tsunamis generate probabilistic distributions from various earthquake scenarios with small to large magnitudes that occur more frequently.

4.2 Buildings Distribution

According to our survey conducted in 2022, there were 82,300 unit of buildings in Banda Aceh. Most of the buildings are C3L-type (concrete frame with unreinforced masonry infill walls) buildings and they were built after the 2004 Indian Ocean tsunami (IOT). Compared to another survey conducted in 2017, there is an increase of around 30% of the buildings.

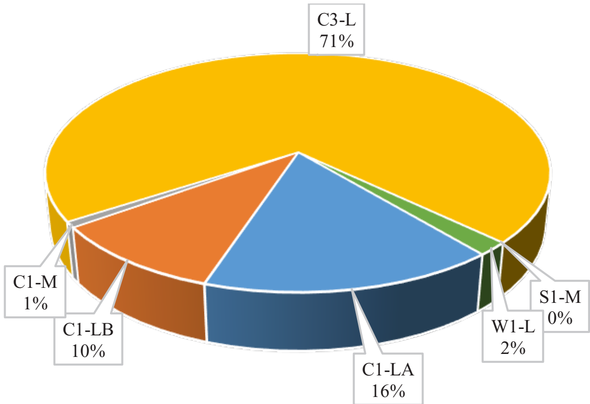

Fig. 5 Percentage number of building identified based on HAZUS.

Fig. 5 shows a pie chart of the buildings identified/clustered in 2022 based on HAZUS classifications. Our study also showed that the number of wooden frame houses have been sharply decreased in the city after the 2004 IOT. The increase was been significantly found within the 2004 IOT inundation area mapped by TDMRC. A new CBD has been introduced after the 2004 IOT. It is located outside of the 2004 IOT inundation area. Apparently, the growth has been seen significant in this area. There are two CBDs in the city, the first one is located about 5 km from the coastline of the city and still being kept as the CBD although growth of buildings around this area is not significant between two set of data (2017 and 2022).

4.3 Impacts on buildings

Fig. 6 and 7 display the maps of building distribution affected by tsunami inundation based on deterministic and probabilistic studies, respectively. These maps show that the majority of buildings with damage are located in post-2004 IOT inundation area.

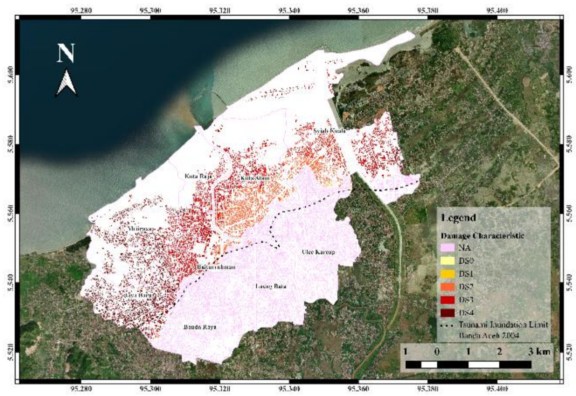

Fig. 6 Buildings Impact Map of Tsunami Based Tsunami 9.2 Mw

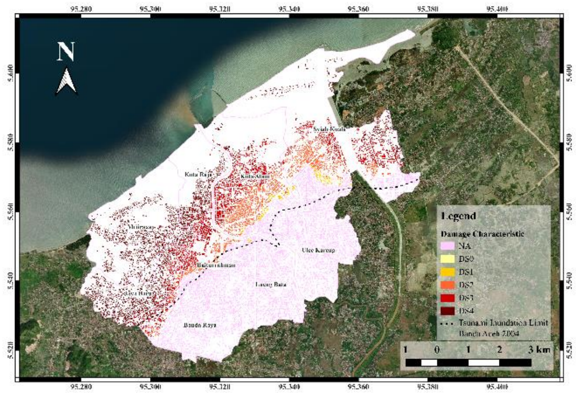

Fig. 7 Buildings Impact Map of Tsunami Based Tsunami 860-years Return Periods

Based on Figs. 6 and 7, which explain the map of the distribution of buildings that have the potential to be affected by the inundation of a 9.2 Mw magnitude tsunami and a tsunami with a return period of 860 years. It can be seen that the impact of damage to buildings on the coast has a greater potential for damage caused by higher tsunami inundation. Regarding the comparison between the two types of tsunami inundation presented, there are differences in the potential damage to buildings. Tsunami inundation with a magnitude of 9.2 Mw is characterized by large waves and has impacts that include serious physical damage to buildings.

However, when compared to tsunami inundation with a return period of 860 years, it appears that this inundation is equally or more likely than the 9.2 Mw return period. Based on the results of the PTHA calculations which show that the potential damage based on 860 years has a greater damage level than the magnitude of 9.2 Mw. The reality is that inundations with long return periods have the potential to flatten coastal areas in an unprecedented way. This shows that it is important to look beyond tsunami impacts and consider the long-term damage potential.

Based on Fig. 6 and 7, the total number of buildings potentially damaged by a tsunami with a magnitude of 9.2 Mw and a tsunami with a return period of 860 years is calculated, resulting in a distribution graph of potentially damaged buildings. Fig. 8 shows the distribution of the potential damages caused by a-9.2 Mw triggered tsunami from the Aceh-Andaman Sea. The damage ratio of each of the buildings was later taken into account when estimating the economic losses due to the damages.

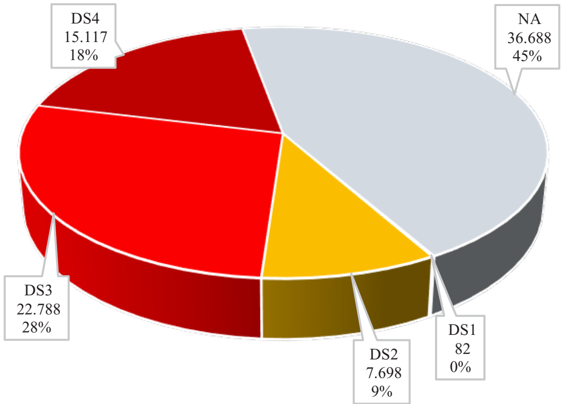

Fig. 8 A pie chart of building damages based on deterministic method.

Fig. 9 shows the distribution of building damages caused by the tsunami probabilistic with an 860-year return period. This damage will be considered as the value to be accounted for in terms of building losses.

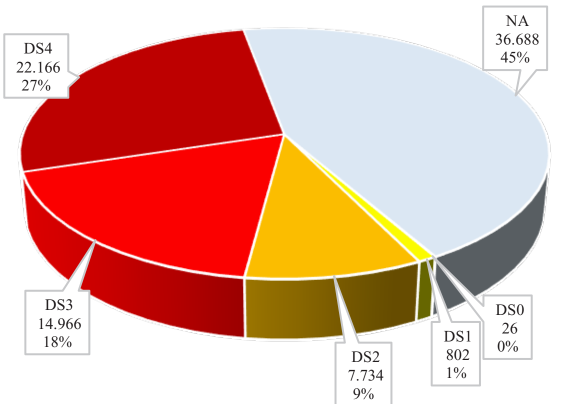

Fig. 9 A pie chart of building damages based on probabilistic method.

Based on Figs. 8 and 9, it can be observed that the comparison between the two levels of damage gives insignificant different results. The number of affected buildings in Banda Aceh accounts for 55% while the unaffected buildings represent 45%. This indicates that the buildings within the 2004 IOT inundation extent still pose serious threats from future tsunami.

Although the ratio between the number of buildings impacted by the two types of inundation is not much different, there are buildings that are potentially spared from the largest simulated tsunami. This is due to a number of factors such as the type of building structure, the location of the building and the geographical location of the buildings. The impacts of both types of tsunami inundation tend to have a heavy level of damage, indicating that tsunami inundation with lower magnitude and return period has a significant impact on some buildings located on the coast.

Based on the deterministic and probabilistic tsunami studies, 45% of the buildings were severely damaged. This illustrates the importance of preparation and mitigation in areas at high risk of tsunami inundation, especially coastal areas. Therefore, mitigation and preparation measures in the face of tsunami threats are needed, both based on probabilistic tsunami analysis and deterministic specific scenarios.

4.4 Losses Probability

The value of building damage in Banda Aceh calculated based on the acquisition value for each building, resulting in the loss value incurred by each building. The total loss for all buildings in Banda Aceh based on deterministic tsunami is 1.95 billion USD, while the total loss for all buildings based on probabilistic tsunami is 1.92 Billion USD. This indicates that the building losses due to the tsunami, based on these two methods, are not significantly different. The results seem to give good agreement for the extent of the study area. However, it is necessary to state that the larger the study area, the more bias results between deterministic and probabilistic.

The assessment of tsunami losses is an important context for understanding the financial impact of a tsunami event. In this study, the loss value of a building is calculated based on the probability of damage to the building multiplied by the acquisition cost of the building. This method makes it possible to provide an overview of the losses incurred by each building individually. The focus of this research is only on providing the magnitude of the financial impact on communities and the government as a result of the tsunami.

In this context, the resulting loss is the loss caused by a tsunami with a magnitude of 9.2 Mw simulated by Tursina et al. [21] and the loss caused by a return period of 860 years. The total loss for all buildings in Banda Aceh based on deterministic tsunami is 1.95 Billion USD, while the total loss for all buildings based on probabilistic tsunami is 1.92 Billion USD. This indicates that the building losses due to the tsunami, based on these two methods, are not significantly different. The results seem to give good agreement for the extent of the study area. However, it is necessary to state that the larger the study area, the more bias results between deterministic and probabilistic.

It should be noted, however, that the focus of this study is only on comparing the financial losses caused by buildings, but other infrastructure could not be calculated due to a lack of the necessary data. The figures also reflect the enormous costs required to repair the damage and restore the area after the tsunami. Although the difference between the two is relatively small, aspects such as the extent of damage to buildings, the impact on human lives and other uncertainties must be considered when assessing disaster mitigation.

The 2004 Aceh tsunami caused a building loss of USD 0.88 billion, which was 32% of the total damage caused by the disaster [22]. The financial losses were not only economic, but also social, psychological and environmental. As a comparison, the 2004 tsunami had an unimaginable impact on the people of Aceh, although financial loss was one aspect of the impact, it illustrated the magnitude of the impact caused by the tsunami disaster. The simulated tsunami losses are a reference and a reminder that the potential threat still exists and that more relevant preventive and preparatory measures are needed.

Fig. 10 illustrates the building losses (based on HAZUS) caused by the tsunami. The figure shows that the losses in Banda Aceh were dominated by C3L, which are located within ~3 km from coastline. The losses based on the scenario gave a lost estimation of about 945 million USD.

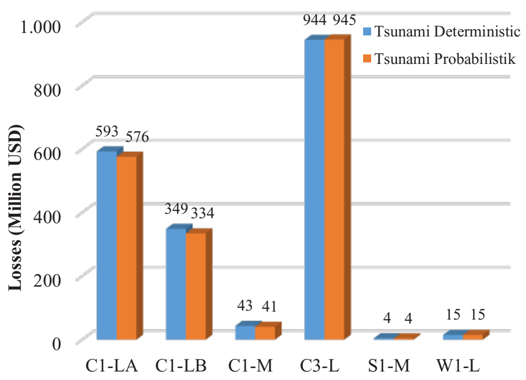

Fig 10. Tsunami losses on building based on HAZUS

From the figure, it can be seen that buildings with a certain load-bearing structure have a different amount of loss, which is influenced by the number of buildings based on that structure and the type of structure that causes the amount of damage and loss. In this case, the focus is on several different types of structures. Each type of structure has different resilience characteristics in dealing with tsunami hydrodynamic.

Deterministic tsunamis can provide a clear and detailed picture of the tsunami impact of an earthquake scenario, such as wave height, inundation distance, current speed and building damage. Deterministic tsunamis can also be used to design tsunami evacuation and mitigation plans, as well as to conduct simulations and community preparedness exercises. However, deterministic tsunamis have limitations in accounting for uncertainties and variations in earthquake sources, as well as in describing the frequency or return period of an earthquake scenario.

Probabilistic tsunamis can provide a broad and comprehensive picture of tsunami hazards and risks from various earthquake scenarios that may occur in a region. Probabilistic tsunamis can also be used to determine the level of vulnerability and exposure of areas or buildings to tsunamis, as well as to calculate economic and social losses due to tsunamis. However, probabilistic tsunamis have limitations in providing specific and accurate information about the tsunami impact of an earthquake scenario, as well as in requiring a large number of complex data and assumptions.

5 Conclusions

Based on the assessment conducted using a series of tsunami fragility curves, total losses due to the impacts of tsunami generated by 9.2 Mw from the Aceh-Andaman segment is around 1.95 billion USD based on probabilistic method or 1.92 billion USD based on deterministic model. The results produced from both methods seem to give a fair agreement with the 2004 Indian Ocean tsunami.

Large number of damages were estimated to come from Confine Masonry Type buildings (C3-L) which dominated the building types in Banda Aceh as surveyed in 2021.

Acknowledgements

Authors acknowledge the research grants received to produce this article, namely (1) RISPRO INVITASI I from LPDP of Ministry of Finance of Republic Indonesia title: "*SupeRISKa*: Decision Support System for Disaster Risk Financing and Insurance based on Hazards Characteristics 2021-2024", and (2) a research grant from Centre for Research and Community Services (LPPM) Universitas Syiah Kuala for this research under Scheme *Hibah Pendamping RISPRO* (HPR) year 2023.

References

[1] N. Peiris, 'Vulnerability functions for tsunami loss estimation', in *First European conference on earthquake engineering and seismology, Geneva, Switzerland*, Feb. 2006, pp. 3–8.
[2] W. J. Cousins, M. Nayyerloo, R. J. Van Dissen, and G. N. S. Science, 'Estimated earthquake and tsunami losses from large earthquakes affecting Wellington Region', 2014.
[3] K. Goda and R. De Risi, 'Probabilistic tsunami loss estimation methodology: Stochastic earthquake scenario approach', *Earthquake Spectra*, vol. 33, no. 4, 2017, doi: 10.1193/012617EQS019M.
[4] E. Lahcene *et al.*, 'Characteristics of building fragility curves for seismic and non-seismic tsunamis: case studies of the 2018 Sunda Strait, 2018 Sulawesi–Palu, and 2004 Indian Ocean tsunamis', *Natural Hazards and Earth System Sciences*, vol. 21, no. 8, pp. 2313–2344, Aug. 2021, doi: 10.5194/nhess-21-2313-2021.
[5] A. Ruangrassamee, H. Yanagisawa, P. Foytong, P. Lukkunaprasit, S. Koshimura, and F. Imamura, 'Investigation of Tsunami-Induced

Damage and Fragility of Buildings in Thailand after the December 2004 Indian Ocean Tsunami', *Earthquake Spectra*, vol. 22, no. 3_suppl, pp. 377–401, Jun. 2006, doi: 10.1193/1.2208088.
[6] S. Koshimura, Y. Namegaya, and H. Yanagisawa, 'Tsunami Fragility — A New Measure to Identify Tsunami Damage —', *Journal of Disaster Research*, vol. 4, no. 6, pp. 479–488, Dec. 2009, doi: 10.20965/jdr.2009.p0479.
[7] J. Macabuag and T. Rossetto, 'Towards the Development of a Method for Generating Analytical Tsunami Fragility Functions', *2nd European Conference on Earthquake Engineering and Seismology*, 2014.
[8] R. Soetanto, F. Hermawan, A. Milne, J. U. D. Hatmoko, S. As'ad, and C. He, 'Developing sustainable arrangements for "proactive" disaster risk financing in Java, Indonesia', *Int J Disaster Resil Built Environ*, vol. 11, no. 3, 2020, doi: 10.1108/IJDRBE-01-2020-0006.
[9] Syamsidik, M. D. Al Farizi, Tursina, A. Yulianur, I. Rusydy, and A. Suppasri, 'Assessing probability of building damages due to tsunami hazards coupled with characteristics of buildings in Banda Aceh, Indonesia: A way to increase understanding of tsunami risks', *International Journal of Disaster Risk Reduction*, vol. 90, p. 103652, 2023, doi: https://doi.org/10.1016/j.ijdrr.2023.103652.
[10] S. Doocy *et al.*, 'Tsunami mortality in Aceh Province, Indonesia', *Bull World Health Organ*, vol. 85, no. 4, pp. 273–278, 2007, doi: 10.2471/BLT.06.033308.
[11] C. M. Rubin *et al.*, 'Highly variable recurrence of tsunamis in the 7,400 years before the 2004 Indian Ocean tsunami', *Nat Commun*, vol. 8, p. 16019, 2017, doi: https://doi.org/10.1038/ncomms16019.
[12] X. Wang and P. L. F. Liu, 'Numerical simulations of the 2004 Indian Ocean tsunamis-coastal effects', *Journal of Earthquake and Tsunami*, vol. 1, no. 3, pp. 273–297, 2007, doi: 10.1142/S179343110700016X.
[13] J. J. Wijetunge, X. Wang, and P. L. F. Liu, 'Indian Ocean Tsunami on December 26, 2004: numerical modeling of inundation in three cities on the south coast of Sri Lanka', *Journal of Earthquake and Tsunami*, vol. 2, no. 2, pp. 133–155, 2009, doi: 10.1142/S1793431108000293.
[14] H. Zhou, M. H. Teng, P. Lin, E. Gica, and K. Feng, 'Predicting Run-Up of Breaking and Nonbreaking Long Waves by Applying the Cornell COMCOT Model', in *Nonlinear Wave Dynamics*, P. Lynett, Ed., World Scientific, 2009, pp. 147–163. doi: https://doi.org/10.1142/9789812709042_0007.
[15] X. Wang, 'User Manual for Comcot Version 1.7', 2009.
[16] Syamsidik, M. Al'Ala, H. M. Fritz, M. Fahmi, and T. Mudi Hafli, 'Numerical simulations of the 2004 Indian Ocean tsunami deposits' thicknesses and emplacements', *Natural Hazards and Earth System Sciences*, vol. 19, no. 6, 2019, doi: 10.5194/nhess-19-1265-2019.
[17] S. Koshimura, T. Oie, H. Yanagisawa, and F. Imamura, 'Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from banda aceh, Indonesia', *Coastal Engineering Journal*, vol. 51, no. 3, pp. 243–273, 2009, doi: 10.1142/S0578563409002004.
[18] D. L. Wells and K. J. Coppersmith, 'New Empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement', *Bulletin of the Seismological Society of America*, vol. 84, no. 4, pp. 974–1002, 1994.
[19] A. Suppasri, I. Charvet, K. Imai, and F. Imamura, 'Fragility curves based on data from the 2011 Tohoku-oki tsunami in Ishinomaki city, with discussion of parameters influencing building damage', *Earthquake Spectra*, vol. 31, no. 2, pp. 841–868, 2015.
[20] A. Suppasri, E. Mas, S. Koshimura, K. Imai, K. Harada, and F. Imamura, 'Developing Tsunami Fragility Curves from the Surveyed Data of the 2011 Great East Japan Tsunami in Sendai and Ishinomaki Plains', *Coastal Engineering Journal*, vol. 54, no. 1, pp. 1250008-1-1250008–16, Mar. 2012, doi: 10.1142/S0578563412500088.
[21] Tursina, Syamsidik, Kato, S., & Afifuddin, M. (2021). Coupling sea-level rise with tsunamis: Projected adverse impact of future tsunamis on Banda Aceh city, Indonesia. International Journal of Disaster Risk Reduction, 55, 102084. https://doi.org/10.1016/j.ijdrr.2021.102084
[22] Syamsidik, Nugroho, A., Oktari, R. S., & Fahmi, M. (2019). Aceh Pasca 15 Tahun Tsunami: Kilas Balik dan Proses Pemulihan. Tsunami and Disaster Mitigation Research Center (TDMRC) Universitas Syiah Kuala. (Original work published 2019)
[23] Azmeri, Mutiawati, C., Al-Huda, N., Mufiaty, H. Disaster Recovery Indicators of Housing Reconstruction: The story of post tsunami Aceh, Indonesia. *International Journal of Disaster Management*, 1(1), pp35-45, 2017.