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Reconstruction of the Indian Ocean Tsunami in 2004 in Sabang Based on the Current Land Cover for Tsunami Evacuation Sites Recommendations

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Abstract

Sabang City has grown in term of city's population as well as the tourism activity. The development also meant there are more area that has been used when compared to the time before the 2004 tsunami. This research was developed to re-identify tsunami-prone zones with the current land cover condition in Sabang City and to provide recommended safe locations, alternative evacuation routes, and additional evacuation sites. We used Cornell Multi-grid Coupled Tsunami Model (COMCOT) to carried out the tsunami simulation added with updated land cover to provide more accurate simulation model. The simulation pointed out several tsunami hazard zones in Sabang City, such as Balohan, Kuta Ateuh, and Iboih with expected tsunami heights to be more than 3 meters and arrival time less than 60 minutes. Those areas then surveyed to develop recommendations for tsunami risk reductions. The recommendations included nine additional evacuation buildings are proposed, three sites in each zone. Another recommendation is in form of evacuation routes in each zone to complement existing routes stated in RTRW document.

Keywords: *Tsunami Evacuation Sites; Land cover; Sabang; Earthquake; Tsunami*

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INTRODUCTION

The 2004 Aceh earthquake is recognized as the largest natural phenomenon since the 1964 Alaska earthquake [1-5]. A previous study showed the earthquake's seismic moment was 6.5×10^{22}Nm (Mw 9.15) with a rupture duration of 600 seconds [6–9]. According to the Harvard CMT catalog, the earthquake mechanism shows an upward fault pattern (strike = 329°, dip = 8°, rake = 110^0) generated by subduction activity on the west coast of Sumatra. The earthquake caused fractures over 1200 km long, clearly visible from the distribution of aftershocks (Figure 1) [10–13]. Furthermore, the earthquake generated the most devastating tsunami in history, which killed more than 200,000 local people who surrounded the Indian Ocean.

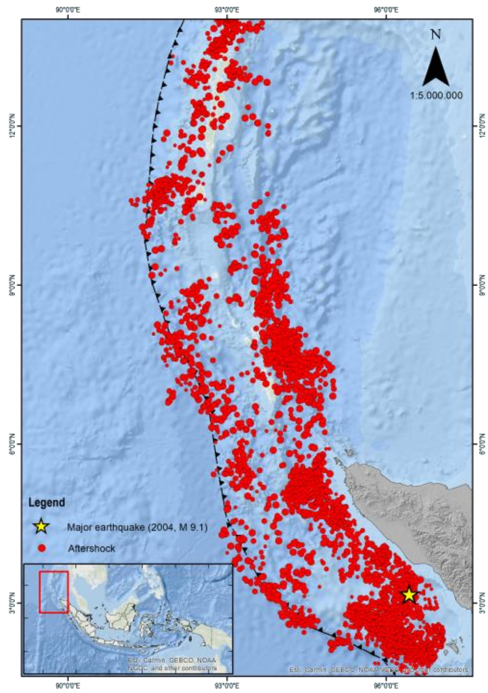


Figure 1. Aftershock Distribution of the Indian Ocean Earthquake in 2004

The tsunami hit almost the entire area, including the City of Sabang, Weh Island. Alluding to the topography, Sabang City typifies a mountainous, hilly, and plain area, with 48.17% of which is mountains, 14.10% hills, and 37.72% plains [14–16]. With these topographical conditions, the city should ideally be classified as an area safe from tsunami disasters. However, the 2004 tsunami brought about an intense impact by claiming as many as ± 200,000 lives [17–20]. In fact, Sabang is also known as Indonesia's maritime gateway, an integrated economic development area, an Indonesian free trade zone, and a tourism city. In 2018, the city was visited by more than 30,000 tourists, equivalent to three-quarters of the population in the City of Sabang itself [21,22]. Since 2018, Statistics Indonesia (BPS) has shown swift population growth in Sabang City. Regarding population, Sabang City was resided by 30,653 people in 2010, which pointed out the increase of 12.78 % of the total population in 2004[22]. This condition requires the Sabang City government to minimize the risk of a tsunami disaster to protect and provide people and tourists with a sense of security in Sabang City.

Research discussing tsunami hazards in Aceh has been carried out for various purposes by many researchers. These include research on tsunami-generating sources, estimated tsunami heights, estimated tsunami arrival times, tsunami disaster mitigation efforts, and traces of tsunamis in the past (*paleo tsunami*) [10,11,18,23–26]. Several topics are generally focused on the West Coast of Aceh and Banda Aceh, while not much has been done for Sabang. Meanwhile, the development of Sabang City every year has the potential to result in changes in spatial and regional planning, so it is necessary to update facilities to minimize the risk of tsunami disasters.

This research was developed to re-identify the tsunami-prone zones with current land cover conditions. As per the fact, the cover of the residential land and public facilities such as ports, hospitals, and schools on the coast are closely related to the high loss of life and property. Currently, based on the Sabang City Government Regulation on Spatial and Regional Planning for 2012-2032, there have been 15 tsunami-prone areas regulated in [21,22]. By looking at the potential for tsunamis that have occurred in Sabang, this research is considered crucial to be carried out. Thus, it is strongly expected to provide a basis for updating preventive efforts to deflate the risk of tsunami disasters, such as recommending safe locations (assembly points), alternative evacuation routes, and additional evacuation sites.

METHOD

The tsunami numerical simulation was carried out using the Cornell Multi-grid Coupled Tsunami Model (COMCOT), which applies both linear and nonlinear shallow water equations (SWEs and NSWEs, respectively) [23,25,27–29]. The equations were solved using the leap-frog staggered scheme as in the Finite Difference Method. In addition, the COMCOT linear shallow water equation in the spherical coordinate system is expressed in Equation 1-3.

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\varphi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}(\cos\varphi\ Q)\right\} = -\frac{\partial h}{\partial t} \tag{1}$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R\cos\varphi}\frac{\partial \eta}{\partial \varphi} fQ = 0, \tag{2}$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \varphi} + fP = 0. \tag{3}$$

Meanwhile, the nonlinear shallow water equation denoted in Equation 4-6.

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\emptyset}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \emptyset}(\cos\emptyset\ Q)\right\} = -\frac{\partial h}{\partial t} \tag{4}$$

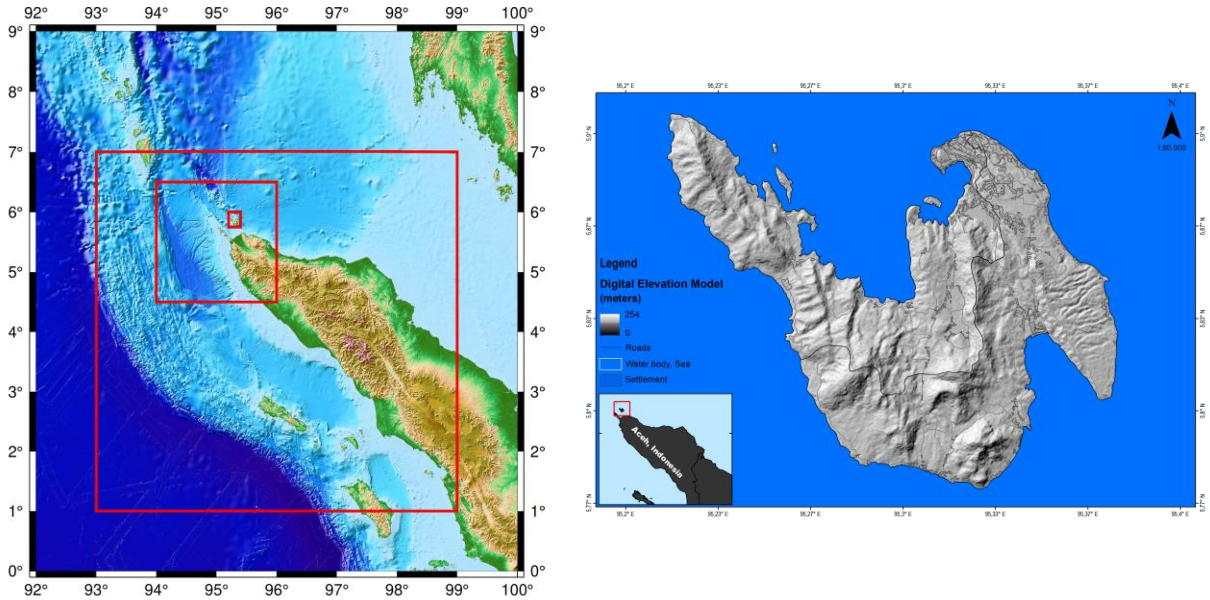
$$\frac{\partial P}{\partial t} + \frac{1}{R\cos\emptyset}\frac{\partial}{\partial \psi}\left\{\frac{P^2}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \emptyset}\left\{\frac{PQ}{H}\right\} + \frac{gH}{R\cos\emptyset}\frac{\partial \eta}{\partial \psi} - fQ + F_x = 0 \tag{5}$$

$$\frac{\partial Q}{\partial t} + \frac{1}{R\cos\emptyset}\frac{\partial}{\partial \psi}\left\{\frac{PQ}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \emptyset}\left\{\frac{Q^2}{H}\right\} + \frac{gH}{R}\frac{\partial \eta}{\partial \emptyset} - fP + F_y = 0 \tag{6}$$

With P serving as the volume flux in the x direction (East-West), Q is referred to as the volume flux in the y direction (North-South), h to the depth of the grid to mean sea level, while (u, v) indicate the velocity in the x and y directions, respectively. Further, η points out the water surface elevation, $(\phi\psi)$ latitude, and longitude in the spherical coordinate system, R for the Earth's radius, while g represents gravity. The $-\partial h/\partial t$ denotes the temporary seafloor movement effect, and the Coriolis force coefficient caused by the Earth's rotation is stated as f. In addition, Ω indicates the Earth's rotation rate, and H is the total water depth. F_x and F_y signify the bottom friction in the ψ and φ directions, respectively. Meanwhile, n denotes Manning's roughness coefficient.

The tsunami numerical simulation produces estimates of tsunami arrival times as well as those of tsunami amplitude and height. The estimated tsunami arrival time is intended to be the time the tsunami arrives at the coastline of the research area. Meanwhile, amplitude is defined as the height of the tsunami wave on the coastline. Meanwhile, tsunami height signifies the height of the tsunami wave on the land. Furthermore, combining all the information provided produces a tsunami hazard map.

In order to achieve a more detailed result, a nesting grid method is conducted by creating four grids with Sabang and Weh Island as exposure areas. Grids, commonly mentioned as layers, are illustrated in Figure 2. The latest land cover variation is also considered in tsunami numerical simulation. In Weh Island, Sabang is covered by river, sea, settlement, and coastal vegetation. The land cover variation of Sabang, Weh Island, as shown in Figure 3, represents the roughness coefficient in tsunami modeling (Table 1).



(a) (b)

Figure 2. (a) Grids or Layers of Numerical Tsunami Simulation Schema. Exposure (Red Box, Layer 1-3) Area of Tsunami Numerical Simulation Model in SABANG. (b) The Land Cover Existing in Sabang City

Table 1. Manning Roughness for Coefficient Land Cover for Tsunami Numerical Modeling [23,25,28]

Land cover	Manning roughness
Water area, Roads	0.025
Middle density residential area	0.050

Moreover, topographic data based on the digital elevation model (DEM), sea level model data (bathymetry), and data obtained from the Geospatial Information Agency (BIG, Indonesia) were also used to support numerical simulations of tsunamis. Bathymetry data for Layers 1–4 were retrieved from BATNAS with a resolution of 180 meters in all scenarios (https://tanahair.indonesia.go.id/demnas/#/batnas). Meanwhile, Digital Elevation Model (DEM) data from DEMNAS with a resolution of 8 meters were also adopted for land topography data (https://tanahair.indonesia.go.id/demnas/#/demnas).

In addition to constructing a multilevel layer model, a numerical tsunami simulation was carried out with an earthquake as a generator, which was assumed to be a fault plane (Figure 4) [23,26–32]. The fault plane model included earthquake hypocenter parameters as shown in Table 2, namely, latitude, longitude, depth, strength (magnitude), strike, dip, slip, and duration of fracture deformation (rupture duration). In this study, the fault plane model adopted was based on the previous research, with the following fault plane model parameters [26] as Table 2.

Table 2. Fault plane model parameters used as a source of tsunami generators.

Sub-fault	Longitude	Latitude	Length	Width	Depth	Strike	Dip
A	2.37	95.55	100	100	10	340	10
B	3.23	95.23	160	100	10	340	10
C	4.45	95.25	150	90	10	340	10
D	5.73	93.80	150	100	10	340	10
E	6.00	94.57	150	100	27	340	10
F	6.87	92.93	150	100	5	340	10
G	7.13	93.70	150	100	22	340	10
H	8.17	92.47	150	100	5	340	10
I	8.43	93.23	150	100	22	340	10
J	9.62	92.40	100	110	10	340	10
K	10.45	95.08	150	110	10	340	10
L	12.03	92.00	100	1125	5	10	10

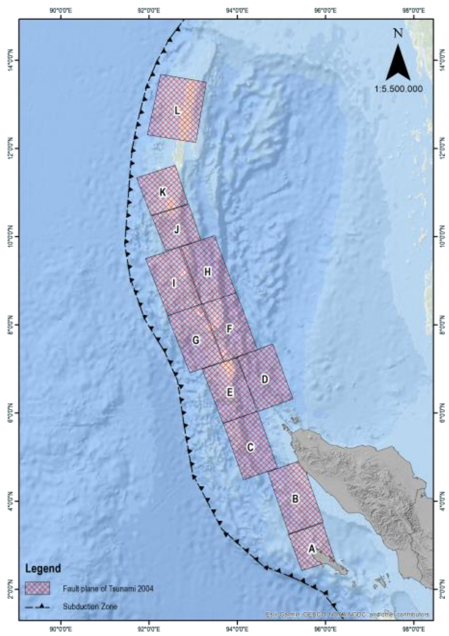


Figure 4. Illustration of a Fault Plane Model in a Tsunami Numerical Simulation [26]

RESULTS AND DISCUSSION

Based on the numerical tsunami simulation results, the tsunami hazard zone in Sabang covers most of Sabang City. In addition, numerical simulations also result in estimates of tsunami arrival times, amplitude, and height. The estimated maximum tsunami amplitude, as illustrated in the yellow bar graph (h> 3 meters) in Figure 5 on the Weh Island coastline, was 8 m. The result is slightly higher than previous studies that mentioned the maximum tsunami height was around 6.6 m [33,34]. The tsunami was modeled by an earthquake with a magnitude of Mw 9.3 (2004 Aceh Earthquake), which was assumed to be divided into 22 fault sub-plots [26]. Referring to the administrative map, the zone with the highest estimated amplitude included 3 areas: Balohan, Kuta Ateuh, and Iboih (Figure 6). Those locations are also known as the worst-affected areas due to the 2004 Aceh tsunami. Besides, the locations are prone to tsunamis based on the spatial planning documents for the City of Sabang for 2012-2032 [22].

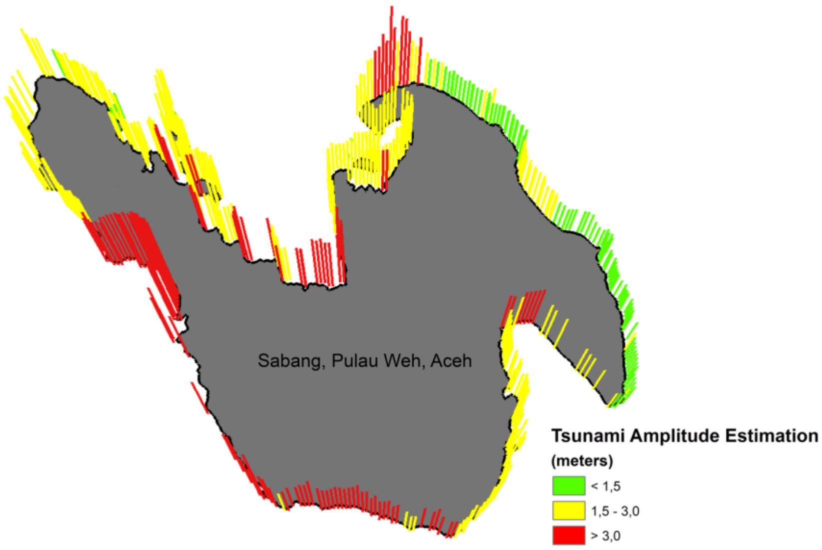
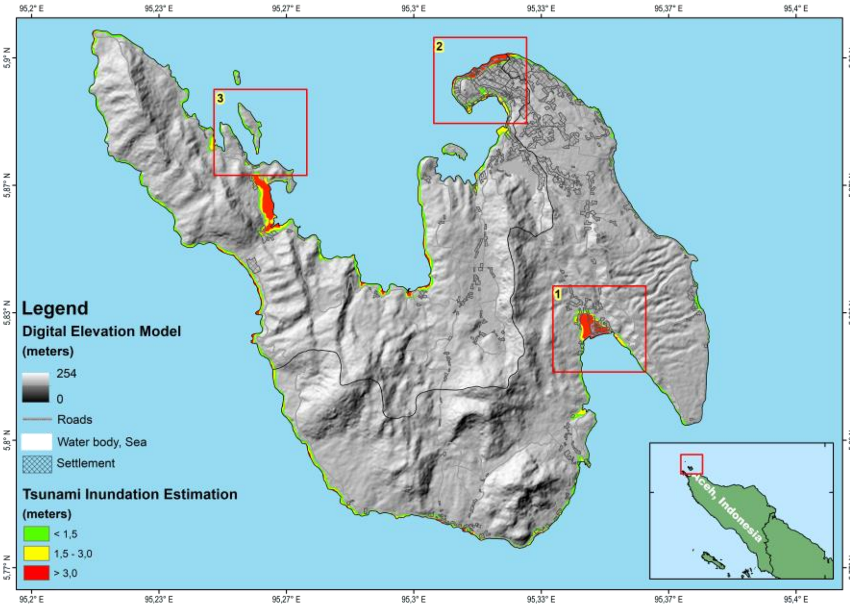
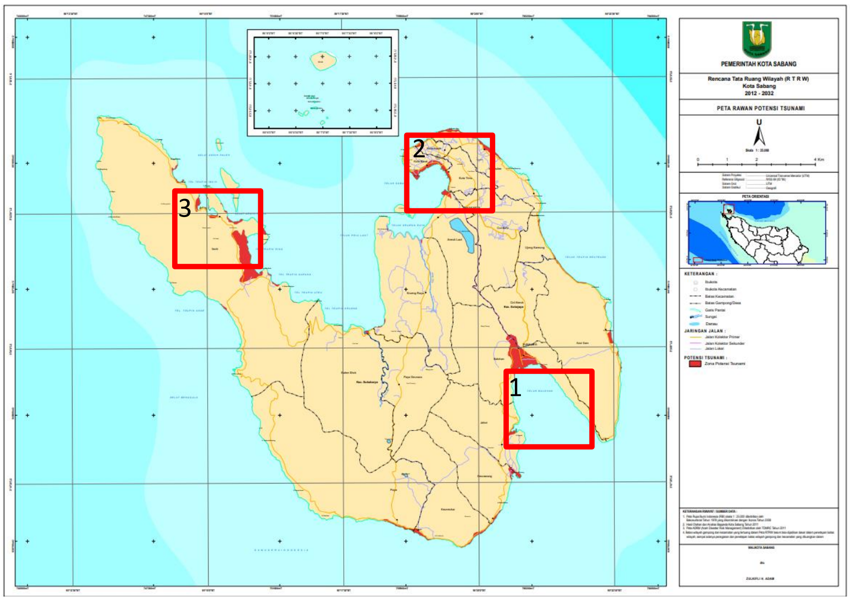


Figure 5. Tsunami Amplitude Map of Sabang city. The Maximum Amplitude of the Tsunami was 8 Meters Relative to The Mean Sea Level

Meanwhile, the estimated tsunami height, as illustrated by the tsunami inundation map (Figure 6a), explains that the tsunami hazard zone covers 3 out of the 14 potential tsunami hazard areas in the RTRW of the Sabang City Government for the 2012-2032 period (Figure 6b), including Balohan, Kuta Ateuh, and Iboih [21,22]. The three affected areas are also known as densely-populated areas, with Balohan resided by 2,527 people and Kuta Ateuh 4,346 people. Meanwhile, Iboih, with 696 people in total, is known as a tourist spot that has the potential for a short-term population increase. Moreover, the height of the tsunami in the three locations reached 5-8 meters above the ground (topography).



(a)



(b)

Figure 6. (a) Tsunami inundation map of Sabang city. There are three areas of high tsunami inundations shown in the red box i.e., Balohan (1), Kuta Ateuh (2), and Iboih (3). (b) Meanwhile, based on Urban Plan of Sabang city for 2021-2032, it is also indicated that these three locations are tsunami potential zones (red zone)

In addition to the amplitude and height of the tsunami, the numerical simulation also generated an estimate of the arrival time of the tsunami at the exposure area. In fact, the estimated arrival time of the tsunami was calculated from the height of the tsunami, reaching 0.5 meters from the average sea level [10,28]. The estimated arrival time of the tsunami in Sabang City, as shown in Figure 7, constituted 9-12 minutes after the earthquake. Meanwhile, for several cities in Aceh Province, the estimated arrival time for the tsunami varied, i.e., 20 minutes in Banda Aceh, 28 minutes in Aceh Jaya, 35 minutes in Meulaboh, 49 minutes in Tapak Tuan, and 56 minutes in Aceh Singkil. It is insignificantly different from the results of previous research, where almost every part of the western areas of Aceh Province had shown an estimated tsunami arrival time of under 60 minutes, except in Tapak Tuan and Aceh Singkil areas [10,35]. The differences in estimated tsunami height and arrival time managed to occur due to data differences, such as earthquake source models, roughness coefficients, and image resolution of digital elevation models and bathymetry used. Basically, the modeling fairly corresponds to several previous studies in Sabang. Based on the estimated arrival time and height of the tsunami, the tsunami potential for Kota Sabang was classified as a MAJOR WARNING with an arrival time of under 60 minutes and a tsunami height above 3 meters (BMKG, 2010). In more detail, some locations with MAJOR WARNING or prone to tsunamis with a height reaching >3 m (h > 3 m) comprised Balohan, Kuta Ateuh, and Iboih as per the spatial planning document for the City of Sabang for the 2012-2032 period. For a more detailed study, additional modeling with Balohan, Iboih and Kuta Ateuh as the exposure areas was carried out, as shown in Figure 6.

Table 3. Fault plane model parameters used as a source of tsunami generators [2,10,11]

Wave height	Tsunami arrival time / Status	
	<60 minutes	**>60 minutes**
0.5 meters	ALERT	ALERT
0.5 meters < h < 3 meters	WARNING	ALERT
h >3 meters	MAJOR WARNING	WARNING

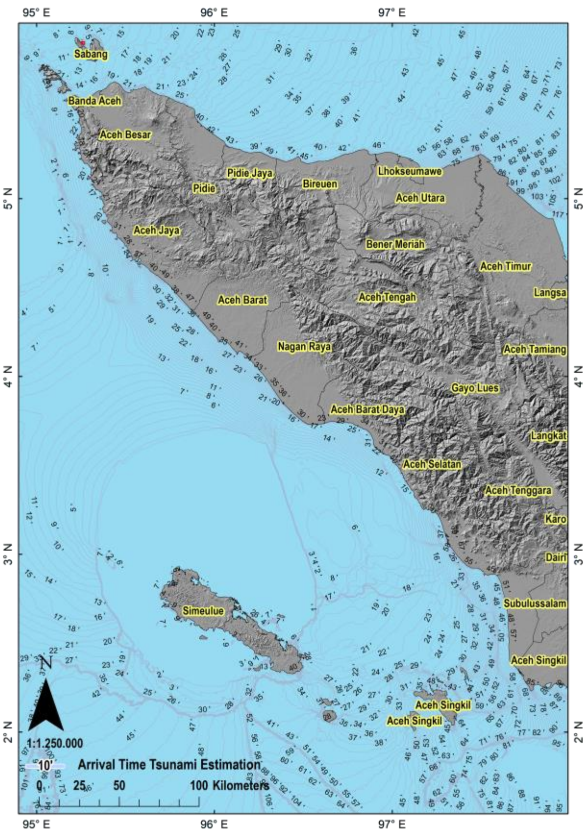


Figure 7. Estimation of Tsunami Arrival Time Map

Balohan

For Balohan, the tsunami inundation zone (Figure 8) includes several vital buildings such as ports, settlements, and schools. Based on the RTRW of the Sabang city administration for the 2012-2032 period, evacuation sites for the Balohan area include public facilities and open spaces such as the sub-district office, the Balohan health center, and an incline [22]. Meanwhile, for the evacuation route (as shown in Figure 8), the path to the evacuation sites is through the main route (in red line). Balohan, furthermore, is known to have an area of 103.61 Ha with a high population rate and a gulf coast type that is seen to have a greater chance of accommodating a tsunami. Under these conditions, the evacuation site was too far to reach the sub-district office, with the inclining asphalt road. Therefore, numerous alternative evacuation routes are proposed, which can be a reference for the community. Alternative routes into the Balohan inundation map were drawn and shown in Figure 8. In addition, they are proposed based on several criteria that have been regulated by the Circular on Tsunami Evacuation Route Planning Guidelines from the Director General of PUPR Number 22 of 2023 [36].

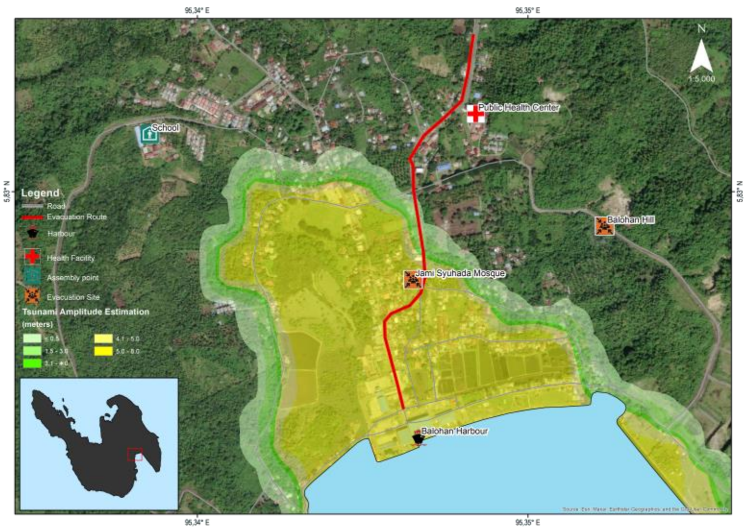


Figure 8. Balohan inundation map. The evacuation route and site in the document of Spatial Planning and Territory (RTRW) of Sabang City (red line). Recommendations of evacuation routes and sites based on the numerical tsunami simulation (green line)

Kuta Ateuh

Kuta Ateuh is known as a massively populated area and the center of government of Sabang City. Therefore, Kuta Ateuh is one of the priorities of the Sabang city government to reduce disaster risks. For tsunami disaster, referring to the RTRW document of the Sabang City Government for the period of 2012-2032, the Kuta Ateuh area has had 7 tsunami evacuation routes that lead to O. Surapati Street [22]. Further, three tsunami evacuation sites are already potentially used for final assembly points, i.e., the Great Mosque of Babussalam, Yos Sudarso Field, and the Playground Field. As per the Kuta Ateuh inundation map (Figure 9) and topography of Kuta Ateuh, Sabang Hill constitutes an elevated area suitable for an evacuation site. As routes to its top are also relatively accessible, Sabang Hill is finally proposed as an alternative evacuation site for the community.

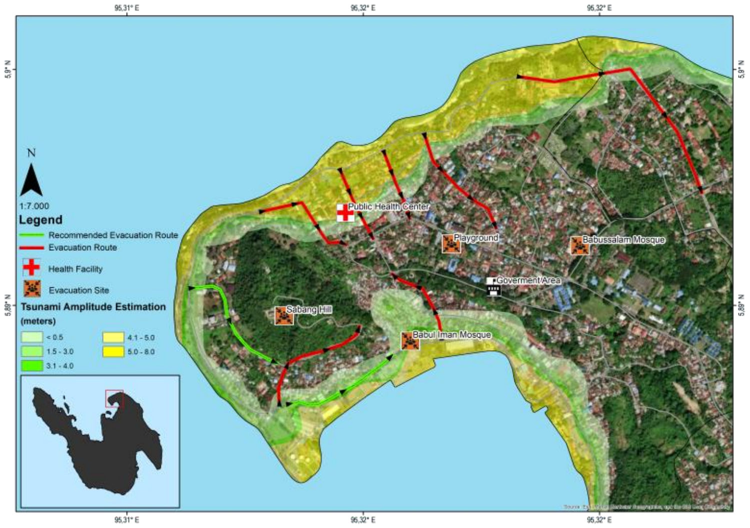


Figure 9. Kuta Ateuh Inundation Map. The evacuation route and site in document of RTRW Sabang City (red line). Recommendations of evacuation routes and sites based on the numerical tsunami simulation (green line)

Iboih

Iboih, one of the tourism areas as well as icons of Sabang City, is regulated in the RTRW of the Sabang City Government for 2012-2032 [22]. The main plan is to occupy public facilities such as village offices and mosques as evacuation sites. Unlike in the Balohan and Kuta Ateuh Areas, Iboih only has a single route in and out of the area. Thus, for the evacuation route, the path will be through the main route leading to the evacuation site, as shown in Figure 10. Iboih is also affiliated with Rubiah Island, which is also set as a tourism destination for domestic and foreign tourists. Access to Rubiah Island only uses a small boat via the Teupin Layeu Harbor in Iboih. Unfortunately, Rubiah Island is excluded from the prioritized areas that have to receive attention as the potentially damaged area even though it is as prone as the Iboih area to tsunamis in addition to having a lack of access to evacuation. Thus, a hill on Rubiah Island is recommended as one of the evacuation sites, with the Garuda Monument as the extra evacuation site in Iboih.

Figure 10. Iboih Inundation Map. Recommendations of evacuation routes and sites based on the numerical tsunami simulation (green line)

Tsunami evacuation site recommendations

In brief, the tsunami evacuation site recommendations in Sabang City are written in Table 4. The tsunami evacuation site recommendations, such as buildings and hills, are chosen based on several criteria following the Indonesian National Standard [11]. The alternative evacuation sites need to meet the Indonesian National Standard (SNI) as follows: (1) the location altitude is higher than the tsunami's height; (2) the building is earthquake-resistant and far from material flow potential or collapsed buildings; (3) the site is government-owned (public buildings) or privately-owned, but still allowed to be used as evacuation sites. Besides referring to Indonesian National Standard criteria, an extra criterion is also supplemented for a recommendation that the sites for evacuation must be connected with fast and easily accessible routes.

Table 4. Evacuation Site Recommendations

No	Building name	Latitude	Longitude	Area	Picture
1	Jami Syuhada Mosque	5.8313	95.3469	Balohan	
2	Balohan Hill	5.8264	95.3582	Balohan	
3	SMP N 3 Sabang	5.8351	95.3393	Balohan	
4	Sabang Hill	5.8914	95.3133	Kuta Ateuh	
5	Babussalam Mosque	5.9007	95.3170	Kuta Ateuh	

No	Building name	Latitude	Longitude	Area	Picture
6	Playground Area	5.8939	95.3196	Kuta Ateuh	
7	Rubiah Island	5.8817	95.2581	Iboih	
8	Garuda Monument (*Tugu Garuda*)	5.8723	95.2549	Iboih	
9	Tuha Babul Ibad Mosque	5.8726	95.2566	Iboih	

The recommended evacuation sites are one of the final products of tsunami modeling that requires accurate topography and coastline typology data. Based on those data, tsunami modeling can result in an ideal estimation of tsunami wave heights and travel time. However, using high-resolution data, such as the primary model of bathymetry and topography, will generate a better estimation of tsunami wave heights and travel time.

By improving topography and bathymetry data, it is strongly expected that the simulation of incoming tsunami waves can be of better accuracy. Based on these results, it is also hoped that understanding will be improved, not only about how to deal with disasters but also how to care for physics, especially in terms of wave mechanics, like the main characteristics of tsunami waves towards various shapes of coastlines.

CONCLUSION

The 2004 tsunami taught us many lessons, primarily about the earthquake cycle. Earthquakes at a specific location have the potential to recur in the future. This research resulted in several tsunami hazard zones in Sabang City, such as Balohan, Kuta Ateuh, and Iboih. According to the RTRW of the City of Sabang, Balohan, and Kuta Ateuh, these areas are potentially affected by tsunamis. Unfortunately, Iboih, the main tourism spot in Sabang City, is not even included in the tsunami hazard zones. As per the results of the tsunami modeling using the latest land cover data in Sabang City, as many as nine additional evacuation buildings are recommended, three of which are located in the Iboih and Rubiah Island areas.

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AUTHOR CONTRIBUTIONS

Abdi Jihad: Conceptualization, Methodology, writing - Original Draft and Validation; Zaenal Abidin Al Atas: Methodology, Formal Analysis; Vrieslend Haris Banyunegoro: Data Curation, Project Administration, and Writing - Original Draft; Herdiyanti Resty Anugrahningrum and Rika Adelina Ginting: Validation and Investigation; Andi Azhar Rusdin, Tommy Ardiyansyah and Tatok Yatimantoro: Funding acquisition.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Bonacho J and Oliveira CS. Multi-Hazard Analysis of Earthquake Shaking and Tsunami Impact. *International Journal of Disaster Risk Reduction*. 2018; **31**: 275–280. DOI: https://doi.org/10.1016/j.ijdrr.2018.05.023.

[2] Grezio A, Marzocchi W, Sandri L, and Gasparini P. A Bayesian Procedure for Probabilistic Tsunami Hazard Assessment. *Natural Hazards*. 2010; **53**: 159–174. DOI: https://doi.org/10.1007/s11069-009-9418-8.

[3] Heidarzadeh M, Ishibe T, Harada T, Natawidjaja DH, Pranantyo IR, and Widyantoro BT. High Potential for Splay Faulting in The Molucca Sea, Indonesia: November 2019 mw 7.2 Earthquake and Tsunami. *Seismological Research Letters*. 2021; **92**(5): 2915–2926. DOI: https://doi.org/10.1785/0220200442.

[4] Small DT and Melgar D. Can Stochastic Slip Rupture Modeling Produce Realistic M9+ Events? *JGR Solid Earth*. 2023; **128**(3): e2022JB025716. DOI: https://doi.org/10.1029/2022JB025716.

[5] Swaroop HL, Yajdani PSk, and Reddy PSRK. Response of Coastal Structures against Tsunami Forces and Its Variation When Impact Load is Applied on Exterior and Interior Columns under Different Soil Conditions. *International Journal of Recent Technology and Engineering (IJRTE)*. 2020; **8**: 1468–1473. DOI: https://doi.org/10.35940/ijrte.E5886.018520.

[6] Subarya C, Chlieh M, Prawirodirdjo L, Avouac JP, Bock Y, Sieh K, et al. Plate-Boundary Deformation Associated with the Great Sumatra-Andaman Earthquake. *Nature*. 2006; **440**: 46-51. DOI: https://doi.org/10.1038/nature04522.

[7] Triyoso W and Sahara DP. Seismic Hazard Function Mapping Using Estimated Horizontal Crustal Strain Off West Coast Northern Sumatra. *Frontiers in Earth Science (Lausanne)*. 2021; **9**: 558923. DOI: https://doi.org/10.3389/feart.2021.558923.

[8] Puspito NT and Gunawan I. Tsunami Sources in the Sumatra Region, Indonesia and Simulation of the 26 December 2004 Aceh Tsunami. *ISET Journal of Earthquake Technology*. 2005; **42**(4): 111-125. Available from: https://iset.org.in/public/publications/75578_459.pdf.

[9] Puspito NT and Gunawan I. Comparison of Two Different Earthquake Sources for the 26 December 2004 Aceh Tsunami Simulation. *Journal of Engineering and Technological Sciences*. 2006; **38**(1): 51-77. DOI: https://doi.org/10.5614/itbj.eng.sci.2006.38.1.5.

[10] Jihad A, Muksin U, Syamsidik, Suppasri A, Ramli M, and Banyunegoro VH. Coastal and Settlement Typologies-Based Tsunami Modeling Along the Northern Sumatra Seismic Gap Zone for Disaster Risk Reduction Action Plans. *International Journal of Disaster Risk Reduction*. 2020; **51**: 101800. DOI: https://doi.org/10.1016/j.ijdrr.2020.101800.

[11] Jihad A, Muksin U, Syamsidik, Ramli M, Banyunegoro VH, Simanjuntak AVH, et al. Tsunami Evacuation Sites in The Northern Sumatra (Indonesia) Determined Based on The Updated Tsunami Numerical Simulations. *Progress in Disaster Science*. 2023; **18**: 100286. DOI: https://doi.org/10.1016/j.pdisas.2023.100286.

[12] Qin X, Motley MR, and Marafi NA. Three-Dimensional Modeling of Tsunami Forces on Coastal Communities. *Coastal Engineering*. 2018; **140**: 43–59. DOI: https://doi.org/10.1016/j.coastaleng.2018.06.008.

[13] Gunawan E, Meilano I, Abidin HZ, Hanifa NR, and Susilo. Investigation of The Best Coseismic Fault Model of the 2006 Java Tsunami Earthquake Based on Mechanisms of Postseismic Deformation. *Journal of Asian Earth Science*. 2016; **117**: 64–72. DOI: https://doi.org/10.1016/j.jseaes.2015.12.003.

[14] Akbar H, Afifuddin M, and Rani HA. Infrastruktur Prioritas pada Zona Pariwisata di Kota Sabang dengan Menggunakan Metode Location Quotient (LQ) dan Analytic Network Process (ANP). *Jurnal Teknik Sipil*. 2017; **6**(3): 233-242. Available from: https://jurnal.usk.ac.id/JTS/article/view/9804.

[15] Rani HA, Afifuddin M, and Akbar H. Tourism Infrastructure Development Prioritization in Sabang Island Using Analytic Network Process Methods. *AIP Conference Proceedings*. 2017; **1903**: 070001. DOI: https://doi.org/10.1063/1.5011570.

[16] Achmad A, Burhan IM, Zuraidi E, and Ramli I. Determination of Recharge Areas to Optimize the Function of Urban Protected Areas on A Small Island. *IOP Conference Series: Earth and Environmental Science*. 2020; **452**: 012104. DOI: https://doi.org/10.1088/1755-1315/452/1/012104.

[17] Leelawat N, Latcharote P, Suppasri A, Sararit T, Srivichai M, Tang J, et al. Today in Thailand: Multidisciplinary Perspectives on The Current Tsunami Disaster Risk Reduction. In Y. Dilek, Y. Ogawa, and Y. Okubo. *Characterization of Modern and Historical Seismic–Tsunamic Events, and Their Global–Societal Impacts*. London: Geological Society of London; 2021. DOI: https://doi.org/10.1144/SP501-2019-97.

[18] Lailissa'adah L, Sulastri S, and Syamsidik S. Intergenerational Tsunami Knowledge Transfer Sixteen Years After the Tsunami in Aceh, Indonesia. *KnE Social Sciences*. Dubai: KnE Publishing; 2022: 45-58. DOI: https://doi.org/10.18502/kss.v7i16.12152.

[19] Widiyanto S, Adi D, and Soans RV. Agent-Based Simulation Disaster Evacuation Awareness on Night Situation in Aceh. *IPTEK The Journal of Engineering*. 2022; **8**(1): 36-43. DOI: https://doi.org/10.12962/j23378557.v8i1.a12799.

[20] Iskandar D, Sinar TS, Samad IA, and Gadeng AN. The Values of Natural Disaster Mitigation in Discourse: The True Story of the Acehnese Tsunami Victims. *Forum Geografi*. 2022; **36**(1): 80-90. DOI: https://doi.org/10.23917/forgeo.v35i2.14032.

[21] Pemerintah Kota Sabang. *Qanun No 6 Tahun 2012*. Sabang: Pemerintah Kota Sabang; 2012.

[22] Pemerintah Kota Sabang. *Rencana Tata Ruang Wilayah (RTRW) Kota Sabang Materi Teknis*

Pemerintah Kota Sabang. Sabang: Pemerintah Kota Sabang; 2012.

[23] Tursina, Syamsidik, Kato S, and Afifuddin M. Coupling Sea-Level Rise with Tsunamis: Projected Adverse Impact of Future Tsunamis on Banda Aceh City, Indonesia. *International Journal of Disaster Risk Reduction*. 2021; **55**: 102084. DOI: https://doi.org/10.1016/j.ijdrr.2021.102084.

[24] Satake K and Tanioka Y. Sources of Tsunami and Tsunamigenic Earthquakes in Subduction Zones. In Sauber J. and Dmowska R. (eds). *Seismogenic and Tsunamigenic Processes in Shallow Subduction Zones. Pageoph Topical Volumes*. Basel: Birkhäuser; 1999. DOI: https://doi.org/10.1007/978-3-0348-8679-6_5.

[25] Syamsidik, Rasyif TM, Fritz HM, Idris Y, and Rusydy I. Fragility Based Characterization of Alternative Tsunami Evacuation Buildings in Banda Aceh, Indonesia. *International Journal of Disaster Risk Reduction*. 2023; **88**: 103607. DOI: https://doi.org/10.1016/j.ijdrr.2023.103607.

[26] Tanioka Y, Yudhicara, Kususose T, Kathiroli S, Nishimura Y, Iwasaki SI, et al. Rupture Process of the 2004 Great Sumatra-Andaman Earthquake Estimated from Tsunami Waveforms. *Earth, Planets and Space*. 2006; **58**: 203-209. DOI: https://doi.org/10.1186/BF03353379.

[27] Yeo I, Jung TH, Son S, and Yoon HD. Probabilistic Assessment of Delayed Multi-fault Rupture Effect on Maximum Tsunami Runup along the East Coast of Korea. *KSCE Journal of Civil Engineering*. 2022; **26**: 1-12. DOI: https://doi.org/10.1007/s12205-021-0272-x.

[28] Syamsidik, Al Farizi MD, Tursina, Yulianur A, Rusydy I, and Suppasri A. 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*. 2023; **90**: 103652. DOI: https://doi.org/10.1016/j.ijdrr.2023.103652.

[29] Rasyif TM, Kato S, Syamsidik, and Okabe T. Numerical Simulation of Morphological Changes Due to the 2004 Tsunami Wave Around Banda Aceh, Indonesia. *Geosciences (Switzerland)*. 2019; **9**(3): 125. DOI: https://doi.org/10.3390/geosciences9030125.

[30] Gusman AR, Tanioka Y, and Takahashi T. Numerical Experiment and A Case Study of Sediment Transport Simulation of the 2004 Indian Ocean tsunami in Lhok Nga, Banda Aceh, Indonesia. *Earth, Planets and Space*. 2012; **64**: 3. DOI: https://doi.org/10.5047/eps.2011.10.009.

[31] Oryan B and Buck WR. Larger Tsunamis from Megathrust Earthquakes Where Slab Dip is Reduced. *Nature Geoscience*. 2020; 13: 319-324. DOI: https://doi.org/10.1038/s41561-020-0553-x.

[32] Tanioka Y, Miranda GJA, Gusman AR, and Fujii Y. Method to Determine Appropriate Source Models of Large Earthquakes Including Tsunami Earthquakes for Tsunami Early Warning in Central America. *Pure and Applied Geophysics*. 2017; **174**: 3237–3248. DOI: https://doi.org/10.1007/s00024-017-1630-y.

[33] Syamsidik, Rasyif TM, Suppasri A, Fahmi M, Al'ala M, Akmal W, et al. Challenges in Increasing Community Preparedness Against Tsunami Hazards in Tsunami-Prone Small Islands Around Sumatra, Indonesia. *International Journal of Disaster Risk Reduction*. 2020; **47**: 101572. DOI: https://doi.org/10.1016/j.ijdrr.2020.101572.

[34] NOAA. *National Geophysical Data Center/ World Data Service: NCEI/WDS Global Historical Tsunami Database*. Asheville: NOAA National Centers for Environmental Information;

2018. DOI: https://doi.org/10.7289/V5PN93H7.

[35] Syamsidik, Rasyif TM, and Kato S. Development of Accurate Tsunami Estimated Times of Arrival for Tsunami-Prone Cities in Aceh, Indonesia. *International Journal of Disaster Risk Reduction*. 2015; **14**: 403–410. DOI: https://doi.org/10.1016/j.ijdrr.2015.09.006.

[36] Direktorat Jenderal Bina Marga. *Pedoman Perencanaan Jalur Evakuasi Bencana Alam Tsunami*. Jakarta: Kementerian PUPR; 2023. Available from: https://binamarga.pu.go.id/index.php/konten/ebook_show/nspk/1954_10pbm2023-pedoman-perencanaan-jalur-evakuasi-bencana-alam-tsunami-.