e-ISSN 2580 - 0752

BULLETIN OF
GEOLOGY
Fakultas Ilmu dan Teknologi Kebumian (FITB)
Institut Teknologi Bandung (ITB)

NUMERICAL SIMULATION OF THE 2018 KRAKATAU TSUNAMI GENERATED BY FLANK COLLAPSE AND ASSESSMENT OF TSUNAMI HEIGHT IN PANDEGLANG REGENCY

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Abstract – *This study aims to reconstruct the tsunami event on December 22, 2018, due to the eruption of Anak Krakatau Volcano, which caused a flank collapse and generated an underwater landslide. Then this landslide caused a tsunami that impacted the coast of the Sunda Strait, especially on the coast of Pandeglang Regency. Based on satellite imagery, it is known that the landslide source came from the southwestern part of Anak Krakatau's wall moving down the former caldera wall of the 1883 Krakatau volcanic eruption. The mount grew again and was known as Anak Krakatau Volcano and appeared above sea level in 1929 and continued to grow. Subsequently, several eruptions spewed sediment deposits that had accumulated on the edges and foot of the mount. These sediments increased and became unstable, causing flank collapse and triggering underwater landslides. Several simulation scenarios have been carried out to obtain the best model that can represent the 2018 Anak Krakatau Tsunami with landslide parameters, namely: the volume of the landslide is 0.276 km*^{3}*, the duration of propagation is 410 seconds, the inclination angle is 8.2°, and the length of the landslide trajectory is 3435 meters. The waveform generated as a tsunami source is in the form of wave peaks in the direction of the slide and wave valleys on the back of the slide.*
Furthermore, this wave propagated in all directions but primarily focused on the southwest, i.e., Panaitan Island and Pandeglang Regency. Tsunami simulations show that the tsunami reached: Panaitan Island and Pandeglang Regency at 58-60 minutes, Kota Agung (Lampung) at 42 minutes, and Ciwandan (Banten) at 46 minutes after the landslide with a tsunami height of 5.01m, 0.9 m, and 0.7 m respectively, with a maximum tsunami wave height of 18.6 m on Panaitan Island. Furthermore, it is known that five areas in Pandeglang Regency fall into the high tsunami hazard category with a tsunami height of more than 3 m, namely Panaitan Island, Ujungkulon District, Sumur, Panimbang, and Labuhan. By accurately knowing the distribution of tsunami height and estimating the time of arrival of the tsunami in the affected area and the inundation area, an early warning system and mitigation efforts can be planned, such as spatial planning and other actions.

Key words*: Anak Krakatau tsunami, numerical simulation, flank collapse, underwater landslide, Pandeglang Regency*

Sari – Penelitian ini bertujuan untuk merekonstruksi kejadian tsunami 22 Desember 2018 akibat letusan Gunung Anak Krakatau yang menimbulkan runtuhan tepi sehingga terjadi longsoran bawah laut. Kemudian longsoran ini menimbulkan tsunami yang berdampak disepanjang pesisir Selat Sunda, khususnya di pesisir Kabupaten Pandeglang. Berdasarkan tangkapan citra satelit diketahui bahwa sumber longsoran berasal dari dinding anak Krakatau bagian Barat Daya bergerak menuruni dinding bekas kaldera letusan Gunung Krakatau 1883. Gunung ini tumbuh kembali dan dikenal sebagai Gunung Anak Krakatau dan muncul di atas permukaan laut pada tahun 1929 dan terus membesar. Selanjutnya terjadi beberapa letusan yang memuntahkan deposit sedimen yang menumpuk di tepi dan kaki Gunung Anak Krakatau. Sedimen ini bertambah banyak dan tidak stabil sehingga menimbulkan runtuhan tepi dan memicu longsoran bawah laut. Beberapa skenario simulasi telah dilakukan, sehingga didapatkan model terbaik yang dapat mewakili kejadian Tsunami Anak Krakatua 2018 dengan parameter longsoran yaitu: volume longsor adalah 0,276 km^3, durasi penjalaran longsoran adalah 410 detik, sudut kemiringan longsoran adalah 8,2°, dan panjang lintasan longsoran adalah 3435 meter. Bentuk gelombang yang dihasilkan sebagai sumber tsunami berupa puncak yang searah dengan longsoran dan lembah pada bagian belakang arah longsoran. Selanjutnya gelombang ini merambat ke segala arah namum terfokus ke arah barat daya menuju Pulau Panaitan dan Kabupaten Pandeglang. Simulasi tsunami memperlihatkan bahwa tsunami mencapai : Pulau Panaitan dan Kabupaten Pandeglang pada menit ke 58-60, Kota Agung (Lampung) pada menit ke 42, dan Ciwandan (Banten) pada menit ke 46 setelah longsoran dengan ketinggian

DOI: 10.5614/bull.geol.2023.7.1.4.

tsunami secara berturut-turut 5,01 m, 0,9 m dan 0,7 m, dengan ketinggian gelombang tsunami maksimal 18,6 m di Pulau Panaitan. Selanjutnya diketahui terdapat 5 daerah di Kabupaten Pandeglang yang masuk dalam kategori bahaya tsunami tinggi dengan tinggi tsunami lebih dari 3 m, yaitu Pulau Panaitan, Kecamatan Ujungkulon, Sumur, Panimbang, dan Labuhan. Dengan mengetahui sebaran tinggi tsunami dan waktu tiba tsunami di wilayah terdampak, serta luas rendaman secara akurat maka dapat direncanakan sistem peringatan dini dan upaya mitigasinya dengan penataan ruang serta upaya-upaya lainnya.

Kata kunci: tsunami, Anak Krakatau, simulasi numerik, runtuhan tepi, longsor bawah laut, Kabupaten Pandeglang

1. INTRODUCTION

Although generally tsunami caused by tectonic activities (earthquakes) (IOC, 2019), volcanic activities can also generate a tsunami in the form of tremor vibration that generates landslides or pyroclastic flows into the water. One of the examples is the Anak Krakatau Tsunami on December 22, 2018 (JRC, 2018; Williams *et al*., 2019).

The 2018 Anak Krakatau Tsunami caused significant damage in the surrounding Sunda Strait i.e., the coastal area of Banten and Lampung. Those regions are located at the east and the southwest of Anak Krakatau Volcano. In the case of this tsunami, Pandeglang district suffered the most severe damage. This area was directly hit by the tsunami, due to the absence of any island in front of it that act as a barrier to reduce the wave energy.

On the other hand, the demographic conditions, such as population growth and rapid infrastructure development related to priority tourism areas in Pandeglang Regency (Wartono *et al.*, 2022), have led to a high tsunami vulnerability factor in the region. These conditions indicate that a tsunami hazard study on the coast of the Sunda Strait is essential as a mitigation effort for coastal communities, especially in Pandeglang.

This research also shows that flank collapses and underwater landslides may have represent the mechanism of events that caused the 2018 Krakatau Tsunami.

2. DATA AND METHODOLOGY

The data used in this research is divided into two groups: input data and verification data. The input data includes bathymetry, topography, and landslide information.

Bathymetry data were obtained from the assimilation of BATNAS (National Bathymetry) data with a resolution of 185 m for deep-sea areas and RBI (Rupa Peta Bumi Indonesia) data with a resolution of 12.5 m for shallow water areas. The topography data were also taken from RBI maps sources with a resolution of 12.5 m. Both data were from Geospatial Information Agency (BIG). Bathymetry and topography data were combined and assimilated to become a Digital Elevation Model (DEM) used as an input for model simulation. The verification data used includes the height of the tsunami taken from the results of a field survey conducted by the Indonesian Geological Agency (based on based on "*Tsunami Selat Sunda di Pantai Carita Banten Hingga 5,26 Meter*" article), as well as tide gauge data. Inundation data were taken from the Geological Agency as well.

In this study, there are four levels of domain with 11 simulation regions (**Table 1**). Domain A is the parent grid, Domain B-1 is the region that captures the landslide (Anak Krakatau Volcano), Domain B-2 captures Pandeglang Regency, and Domain B-3 captures along the coast of Serang in the east, up to Cilegon Regency in the west. Domains C-1 to D-2 capture the coastal region of Pandeglang, and Domain C-5 captures Cilegon City. This domain partition (**Figure 1**) aims to accommodate landslide phenomena and provide a clear description of inundation in coastal areas.

Numerical modeling was carried out in this study using COMCOT software (Wang, 2009). The landslide-induced tsunami generation model used is based on the equilibrium equation of the forces acting from steady state

DOI: 10.5614/bull.geol.2023.7.1.4.

along a straight inclined plane (caldera wall) on the seabed (Watts, 1997, 1998; Watts *et al.*, 2003). The propagation of the tsunami was simulated using the non-linear shallow water equation (NSWE) with 2D depth average consisting of the momentum and the continuity equations. The simulation does not consider the effect of tide, sediment transport, wave breaking, and other complex equations. Additionally, the water level condition is assumed to be steady before the simulation (time-step k-1) and the water level is assumed to be steady during the simulation. It causes the initial condition that is applied to the numerical simulation shown in Equation 1:

$$\eta^{k-1} = 0; P^{k-1/2} = 0; Q^{k-1/2} = 0 \quad (1)$$

The development of the landslide-induced tsunami as a tsunami source refers to scenarios that have been carried out by previous researchers, such as Giachetti *et al.* (2012), Williams *et al.* (2019), Grilli *et al.* (2019), and JRC (2018). Based on these mechanisms, we developed several scenarios and found the best model with the landslide parameters as shown in **Table 2.** We determined the starting and ending points of the landslide based on the Landsat imagery captured after the incident (January 11, 2019) (**Figure 1**). Meanwhile, the determination of the landslide angle is based on previous studies (Giachetti *et al.*, 2012) and the vertical section of the bathymetry along the initial and ending points of the landslide. The track length is the distance from the initial point of the landslide to the estimated landslide stop based on the landslide dimensions.

Table 1. Design of Domain Simulation

Domain	Resolution (m)	Ratio to Domain 1	Parent Domain	Cell Size	
				x	y
A	185	1	-	1490	1113
B-1	61.67	3	A	770	730
B-2	61.67	3	A	2109	1341
B-3	61.67	3	A	816	771
C-1	20.56	9	B-2	1401	1329
C-2	20.56	9	B-2	1764	1605
C-3	20.56	9	B-2	1203	1170
C-4	20.56	9	B-2	2124	1470
C-5	20.56	9	B-2	1032	981
D-1	6.85	27	C-3	1494	2052
D-2	6.85	27	C-4	1491	924

Table 2. Landslide Scenario of Krakatau Tsunami 2018

Volume (km^3)	0.276
Length (m)	2.450
Width (m)	1500
Thickness (m)	75
Angle (°)	8.2
Duration (s)	410
Start X Coordinate (°)	105.413
Start Y Coordinate (°)	-6.103
End X Coordinate (°)	105.391
End Y Coordinate (°)	-6.125
Distance (m)	3.435
Velocity (m/s)	8.38

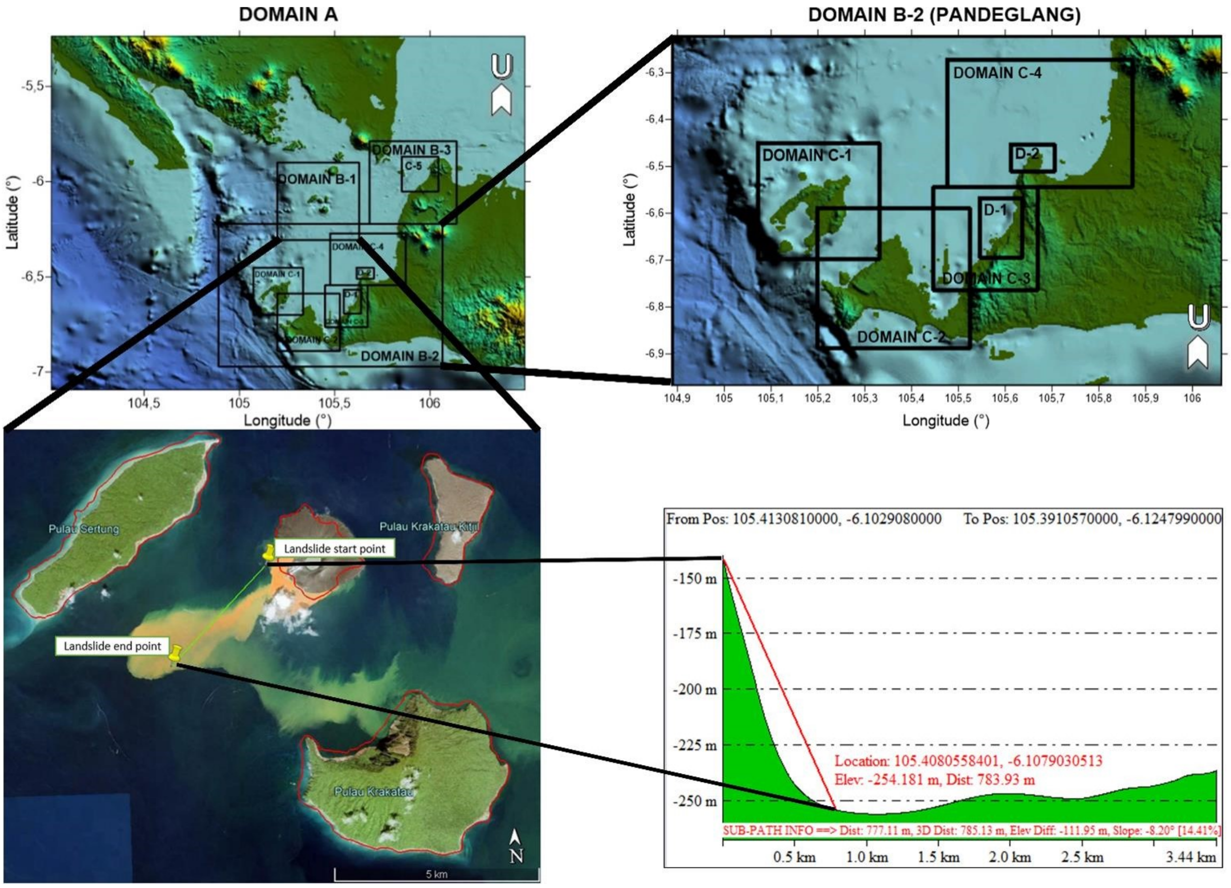

Figure 1. The scenario of domains and landslide scenario used for simulation

In assessing the level of tsunami hazard, the height of the tsunami inundating the land is used as a hazard parameter. Tsunami height classes are divided based on the level of danger to humans and buildings. A higher tsunami elevation will be more dangerous for people and buildings (Latief, 2006).

The tsunami height from the simulation was then normalized at the height of 3 m. The areas that has tsunami elevation >3 m will be given a maximum weight of 1, while the areas that have tsunami elevation ≤ 0.5 m will be given a minimum weight of 0. From the normalization above, the classification of tsunami hazard can be seen in **Table 3** based on tsunami height that attack the area, with dark red color indicating the very dangerous class, red color indicating the dangerous class, orange color indicating moderately dangerous class, and yellow color indicating the less dangerous class.

Table 3. Tsunami Hazard Classification Based on Tsunami Height

Tsunami Height (m)	>3	1,5-3	0,5-1,5	<0,5
Hazard Classification	Very Dangerous	Dangerous	Moderately Dangerous	Less Dangerous

3. RESULTS

Tsunami height data, inundation data, and time arrival data are used to verify numerical simulation results. The tsunami height data from the numerical simulation is statistically compared to the tsunami height data from the field survey at 40 review points on land and 3 review points from water level elevation measurement at the tide station from Williams *et al.* (2019) (review point 47, 48, and 49). Additionally, to identify the wave height oscillation that attacks coastal areas, 6 review points from the sea are used during the simulation (**Figure 2**).

Aida numbers K and κ (Aida, 1978) are used to compare the tsunami height data from the model and the field data in the 43 review points (40 points on the land and 3 tide station point).

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

$$\log \kappa = \left[\frac{1}{n}\sum_{i=1}^{n}(logK_i - logK)^2\right]^{\frac{1}{2}} \quad (3)$$

with,

n = number of observed locations

K_i = $\frac{R_i}{H_i}$

R_i = tsunami height from the field survey in location i

H_i = tsunami height from the numerical simulation in location i

κ = variance of K.

Shuto (1991) proposed a K value of $0.8 < K < 1.2$ (20% error) and $\kappa < 1.45$ (variance tolerance) as a confidence criterion for simulation data. Meanwhile, the Japan Society of Civil Engineers (2002, in Takao *et al.*, 2012) proposed the K value of $0.95 < K < 1.05$ (5% error) and $\kappa < 1.45$ as a confidence criterion for simulation data.

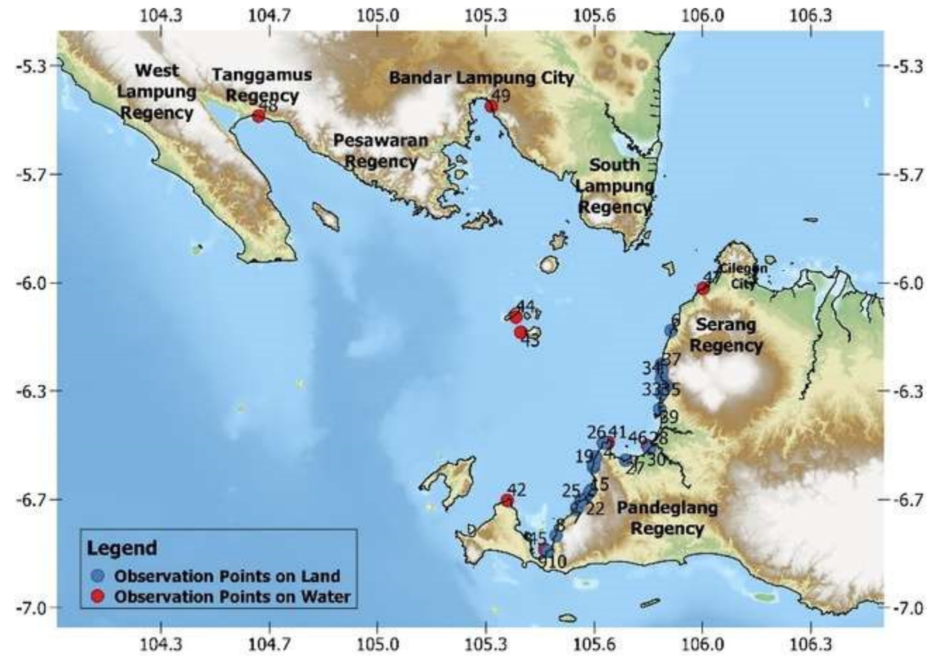

Figure 2. Map of observation points.

The K and κ values from this scenario (based on time-series data comparison) respectively 0.9-0.97 and 1.2-1.3 (**Figure 3**). It shows that the scenario is still within a 5-20% margin of error, and the simulation can be analyzed further. A comparison of inundation data from the simulation and field survey shows that, generally, the simulated tsunami does not inundate the land as far as the real event on December 22, 2018.

Figure 4 shows the tsunami height data along the coastline of Pandeglang Regency overlaid with the field survey data. The tsunami height data depicted is a tsunami height at the coastline and in front of 43 points of review points. The images show that at the border of Panimbang and Babakan Cibeber, the tsunami height from the simulation cannot reach the actual value of tsunami height from the field survey (10.3 m). The simulated tsunami height at the Patia-Carita coastline is overestimated by two review points. It also happens at the Panimbang-Patia coast that one review point underestimate. Meanwhile, the simulated tsunami height at the Cikawung coast to Panimbang varies between being underestimated and overestimated. The height of the tsunami along Serang to Cilegon seems to be decreasing because the distance is getting further from the landslide source and the height varies from 5 meters to 0.5 meters.

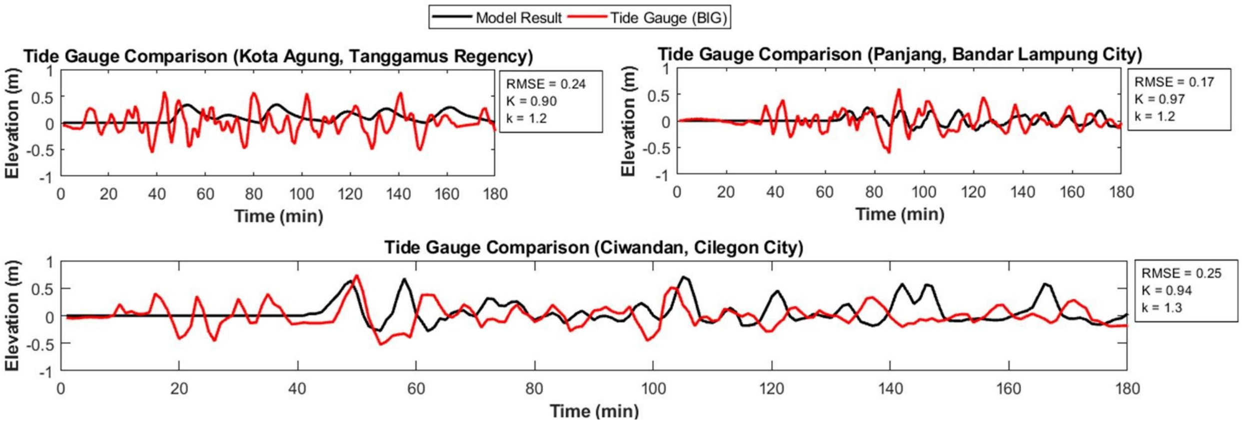

Figure 3. The comparison of tsunami height between simulation and tide gauge at three tide gauge stations (Kota Agung (review point 48), Panjang (review point 49), and Ciwandan (review point 47)).

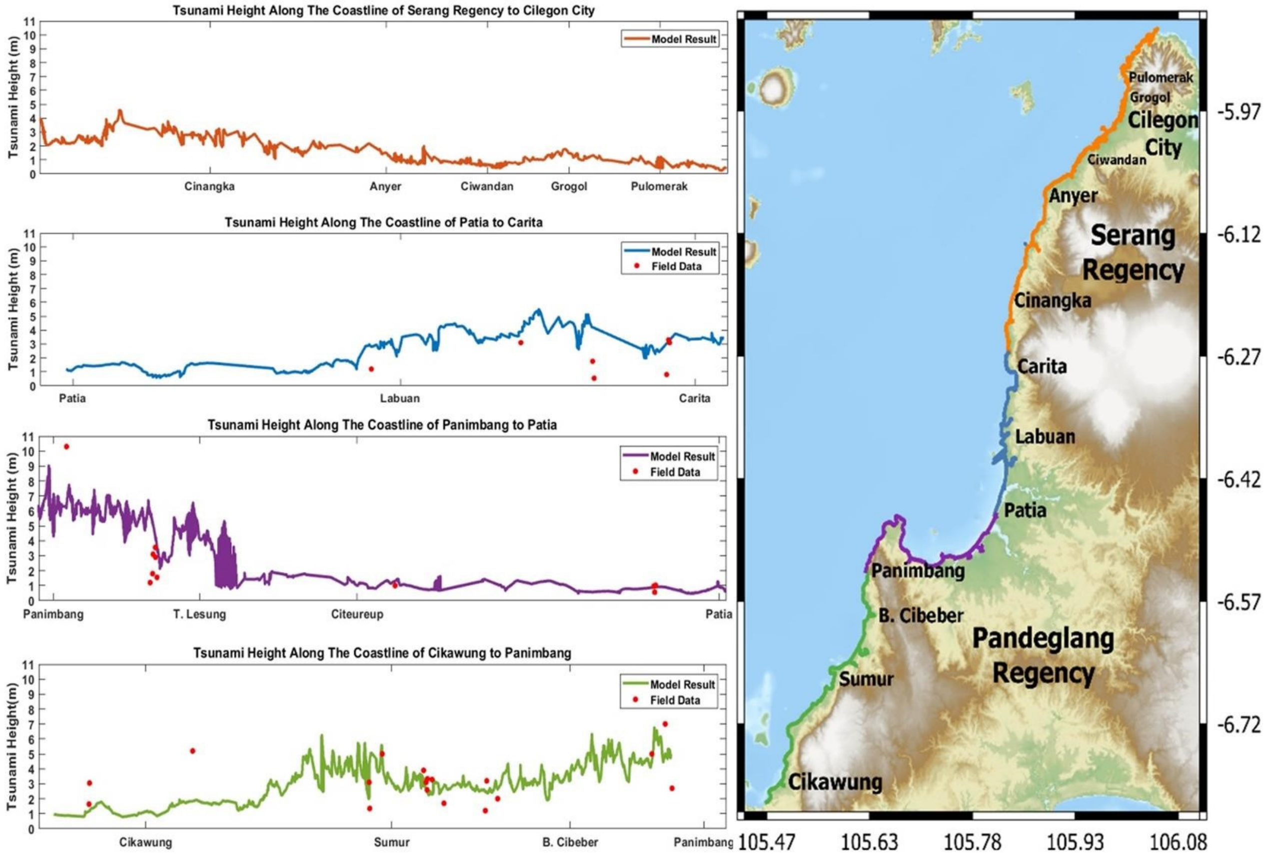

Figure 4. Maximum tsunami elevation along the Pandeglang Regency to Cilegon City and overlaid with tsunami height from a field survey conducted by Indonesian Geological Agency (the red dots). The orange line shows the coastline along Cinangka-Pulomerak sub-district, the blue line shows the coastline along Patia-Carita sub-district, the purple line shows coastline along Panimbang-Patia sub-district, the green line shows the coastline along Cikawung-Panimbang sub-district.

Figure 5 shows the tsunami height map along the coastline that is represented by the bar chart. It shows that the region with high tsunami height (>7 m) is from Panimbang to Tanjung Lesung. However, after Tanjung Lesung, the tsunami height decreased to 2-3 m. Meanwhile, along Citeureup, the tsunami height is <1 m until reaching the Patia region, which has a tsunami height of 1-2 m. Then the tsunami height slightly decreased and increased again at Carita region until it reached a height of 6 m. The Aida number for tsunami height at 43 review points show that the scenario has a 5% margin of error. However, the tsunami height map shows that there are review points that the value is relatively far from the real tsunami height data from the survey. For example, the tsunami height at Panimbang is 10 m from the survey data, but the simulation is only less than 7 m high. Also, considering the arrival time, the simulation result is slower than the data from tide gauge. From these explanations, it can be concluded that underwater landslide is representing the generation of Krakatau Tsunami 2018 because of the Aida number. However, it is expected that there was another mechanism along with it, for example, horizontal forces from the thermal expansion that can cause the simulation result to be 4-11 minutes slower than the tide gauge.

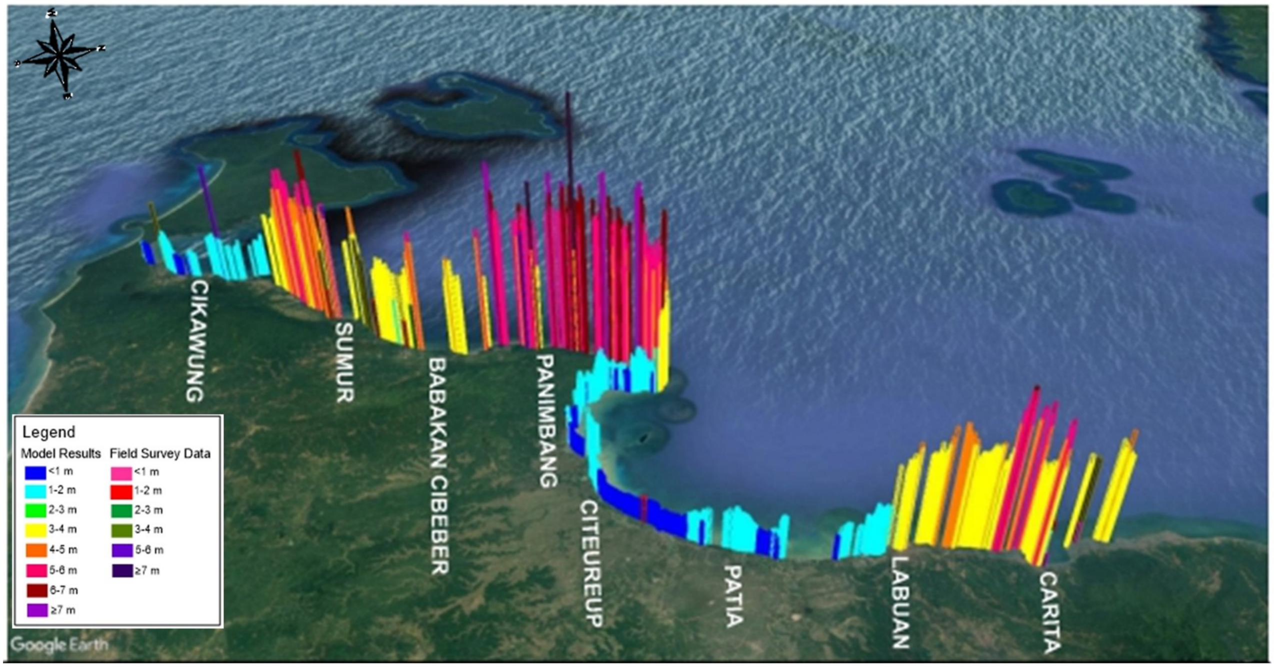

Figure 5. Tsunami height map from the simulation and field survey (Indonesian Geological Agency) along the Pandeglang coast

4. DISCUSSION

The time series of tsunami height is plotted in **Figure 6** at the observation points (review points 44-49) in the Pandeglang Regency, particularly on Panaitan Island, which was the first coastal region affected by the tsunami after the Anak Krakatau Volcano. Meanwhile, the six review points at the sea show that the first tsunami wave is reaching the coast of Tanjung Lesung 58-60 minutes after the landslides (besides Anak Krakatau, with a height of about 5.01 m. Results from those six review points indicate that the highest wave occurred outside of the Anak Krakatau.

Figure 7 shows the spatial plot of tsunami height with a maximum scale of 7 m for all domains, except domain B-1 (**Figure 7b**), which is the region of landslides with a maximum tsunami height at the center of the landslide reaching 87 m, and the 6 m scale used cannot properly visualize this. Spatially, the tsunami height that reached Panaitan Island was 18.6 m (**Figure 7f**). Moreover, the tsunami wave propagates to the southwest along the landslide direction, making Panaitan Island the most devastated region of the tsunami after Anak Krakatau Volcano.

Furthermore, it shows that there were changes in wave direction from the west to north caused by bathymetry conditions that triggerred the

DOI: 10.5614/bull.geol.2023.7.1.4.

wave transformation. The tsunami height map at Tanjung Lesung shows that tsunami flooded the land with an elevation >6 m (**Figure 7j**). It is consistent with the BNPB report that Tanjung Lesung was one of the regions most affected by the Krakatau Tsunami in 2018.

Basically, the first wave of a tsunami generated by an earthquake will be a "trough" due to the underwater deformation. Meanwhile, the first wave of a tsunami generated by a landslide will be a crest because the landslide causes the water elevation to peak and diverge. Watts (1997, 1998) proposed a theory about tsunamis generated by landslide, which starts with a pull-off of water level around the center point of the landslide mass with higher water elevation in the same direction as the landslide. Meanwhile, the lower water elevation will move opposite of the direction of the landslide.

Watts' Theory (1997, 1998) is depicted in **Figure 8** especially in **Figure 8a**. It shows that the maximum tsunami elevation is concentrated at the landslide location at the region of Caldera of 1883 Krakatau eruption or on the southwest of Anak Krakatau Volcano. The figure also shows that around the center point of the initial landslide mass, the water is having a deep "trough" condition, while at the center point of the final landslide mass, the water elevation is having a "crest" and diverges. This pattern is consistent with the landslide pattern, which initially concentrates at one point, then falls off and spreads to the corners.

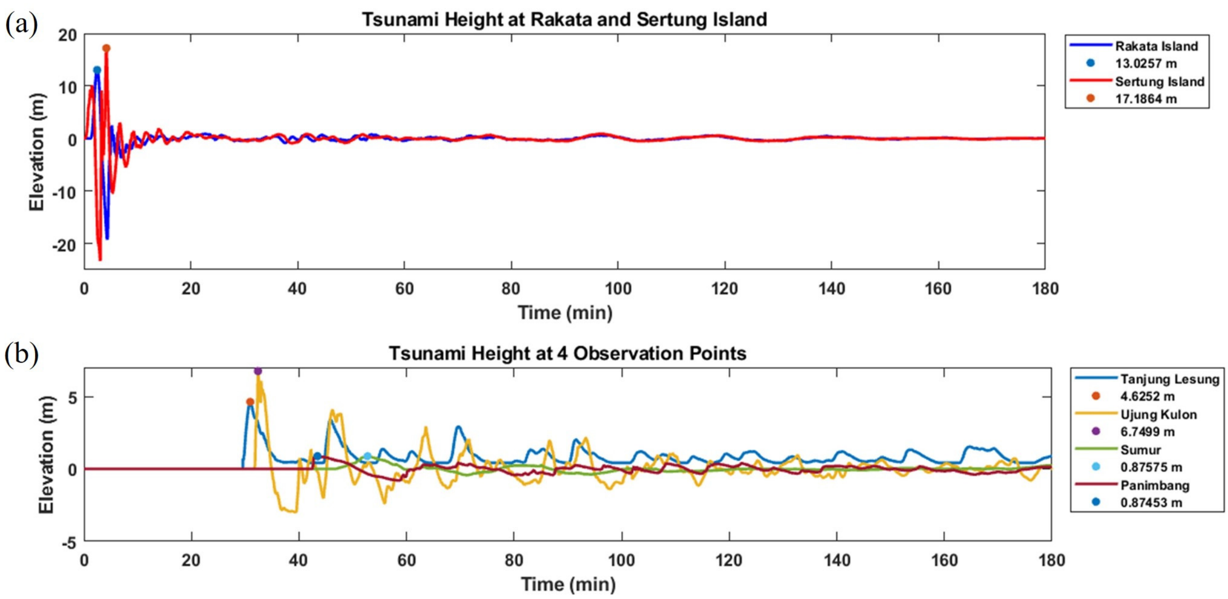

Figure 6. Tsunami height from simulation are shown at: (a) observation point 42 (Rakata Island), and observation point 43 (Sertung Island), (b) observation point 44 (Tanjung Lesung), observation point 45 (Ujung Kulon), observation point 48 (Ujungjaya, Sumur), and observation point 49 (Panimbangjaya, Panimbang).

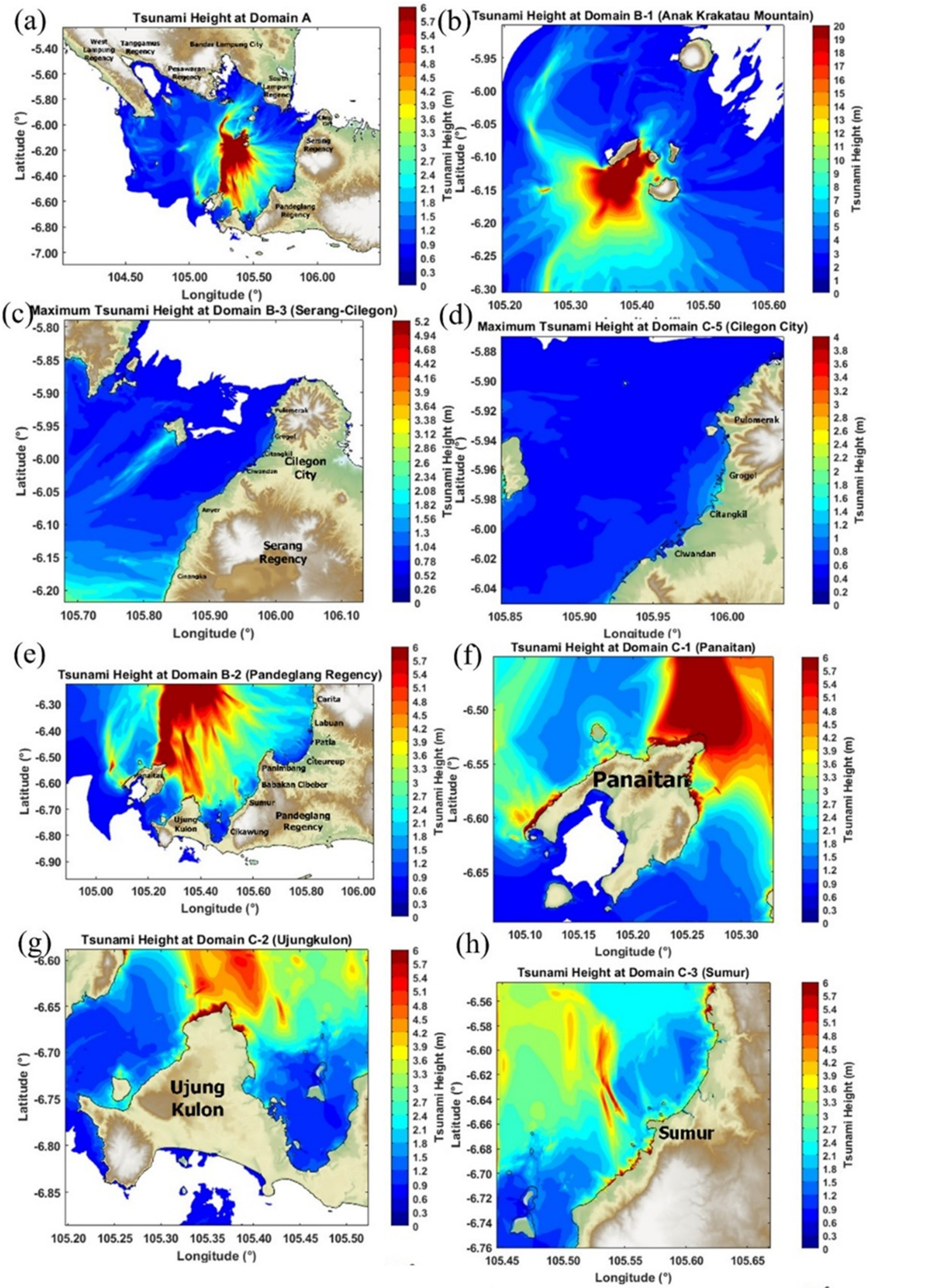

Figure 7. Tsunami height map from the simulation at: (a) Domain A, (b) Domain B-1 (Anak Krakatau Volvano), (c) Domain B-3 (Serang Regency to Cilegon City), (d) Domain C-5 (Cilegon City), (e) Domain B-2 (Pandeglang Regency), (f) Domain C-1 (Panaitan Island), (g) Domain C-2 (Ujungkulon), (h) Domain C-3 (Sumur), (i) Domain C-4 (Panimbang-Labuan), (j) Domain D-2 (Tanjung Lesung).

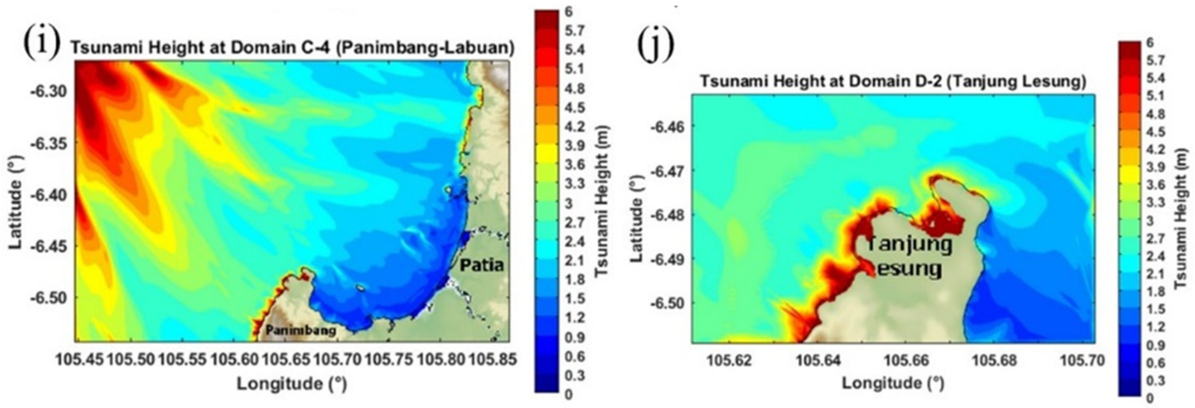

Figure 7. (continued)

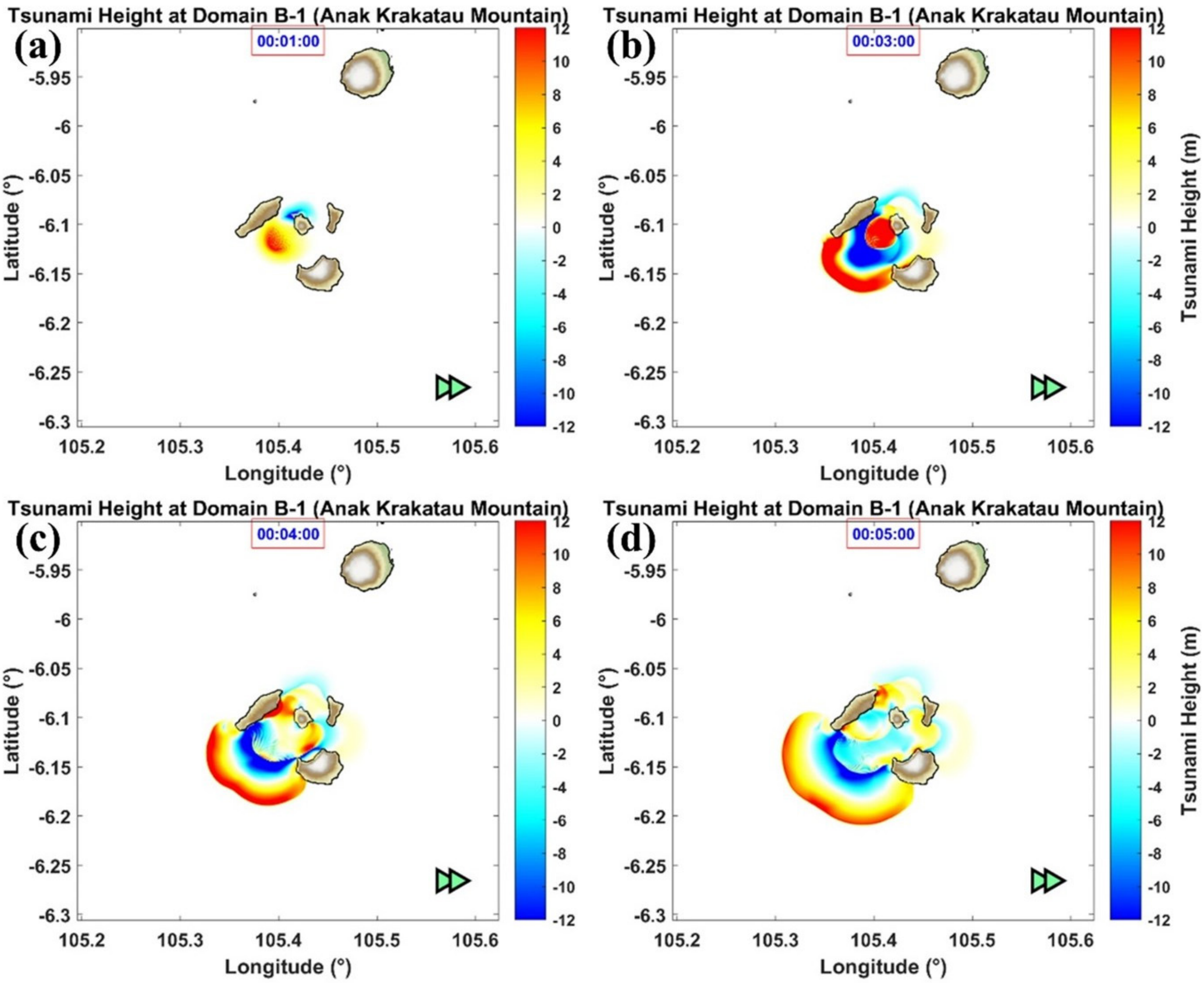

Figure 8. The snapshots of tsunami height at domain B-1 at: (a) 1st minute, (b) 3rd minute, (c) 4th minute, and (d) 5th minute.

Figure 9 shows the tsunami hazard classification based on the height of the tsunami that impacted the coastal area of Pandeglang Regency. Generally, regions with tsunami heights greater than 3m are concentrated at Panaitan, Ujungkulon, and Panimbang (especially Tanjung Lesung). Meanwhile, specific regions such as Cikawung and the area adjacent to Tanjung Lesung until Labuan have a low hazard to the Krakatau

DOI: 10.5614/bull.geol.2023.7.1.4.

Tsunami 2018. This is because these regions are "bay-like" and the tsunami cannot reach them. Additionally, the simulation only covers a period of 2 hours, so there is no inundation in those regions because it took more than 2 hours for the tsunami to reach them. As it comes ashore, the hazard criteria will be lower because the incoming wave will be lower (already muffled), as shown in **Figure 9**.

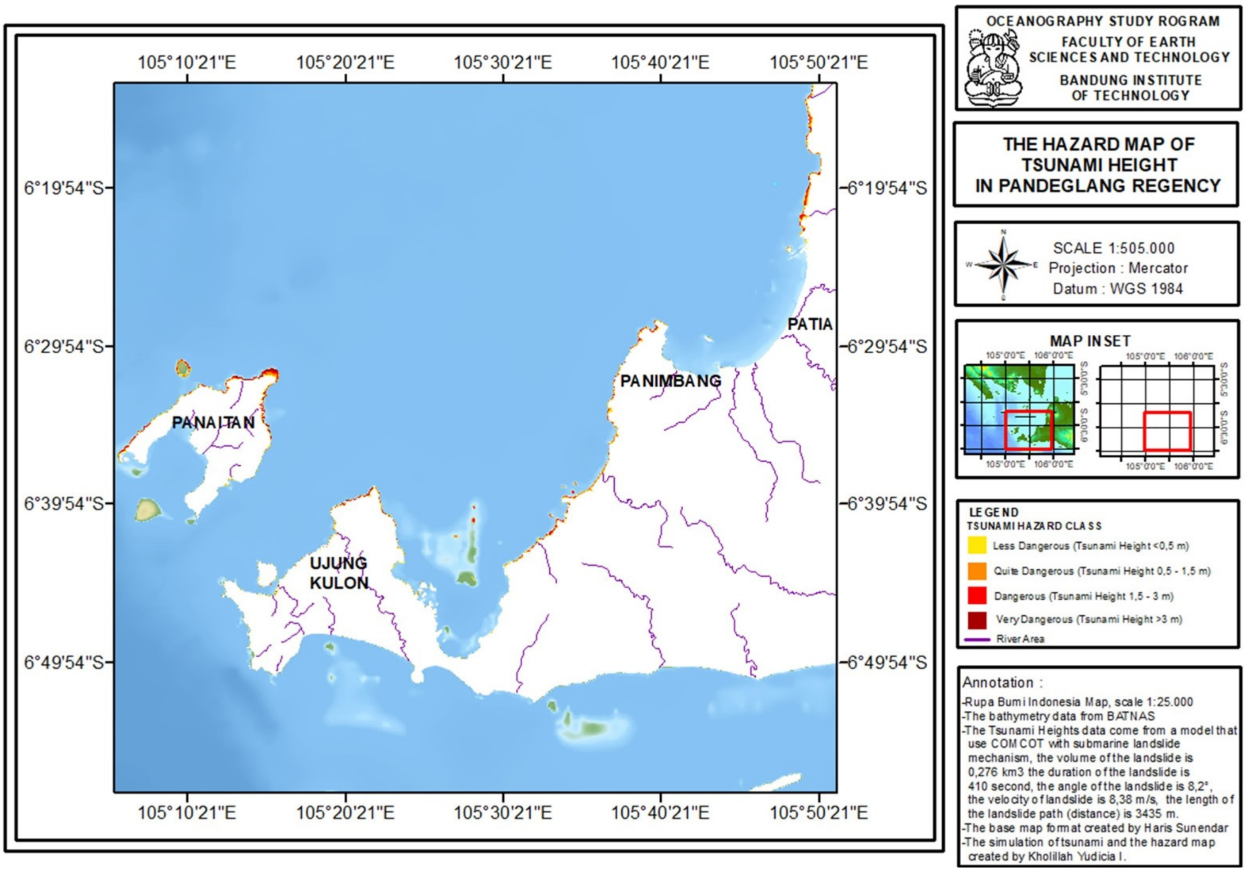

Figure 9. Tsunami hazard map of Pandeglang Regency based on numerical simulation.

5. CONCLUSION

The simulation result with a landslide volume of 0.276 km^3 (L=2450 m, W= 1500 m, H= 75 m), landslide duration of 410 s, landslide angle of 8.2°, and landslide track of 3435 m resulted in a tsunami height that close to the survey data with a margin error of 5%. This simulation result could be further analysed. The tsunami wave propagated to the south-west, causing the tsunami height to reach 18.6 m at Panaitan Island. Pandeglang Regency, Panaitan Island, Ujungkulon, and Tanjung Lesung are classified as dangerous areas. There is a margin error in this research compared to the field survey data, caused by low-resolution DEM data and other mechanisms (other than an underwater landslide) that occurred with the Krakatau Tsunami 2018.

ACKNOWLEDGMENT

This research was funded by the P3MI for Research Group of Oceanography, FITB, ITB entitled “Study of Tsunami Hazard Potential in the Sunda Strait by the volcanic activity of Anak Krakatau Volcano and the Southwest Java-Sumatra subduction earthquake” in 2019. Field Survey support by LPPM-ITB and Research Center for Disaster Mitigation, ITB.

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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