The Mount Anak Krakatau landslide scenario for tsunami modeling in Banten

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Abstract. The eruption of Mount Anak Krakatau occurred on December 22, 2018, in the Sunda Straits, Indonesia, causing a tsunami that affected the coastal area of Banten Province. We use COMCOT 1.7 to make a tsunami model based on flank collapse caused by a landslide tsunami. The aim of study is to remodel past events to anticipate the mechanism and impact of the damage in the future. Bathymetry and topography are integrated to become high resolution data with a grid area of 49.8 meterss. The flank collapse scenario is applied with slide dimensions of 2000 meters long, 1500 meters wide, and 228 meters thick following previous study. The tsunami model consists of the initial tide model and the coastal model. The highest tsunami run-up of the tide model is in Carita of 1.9 meters height. The fastest arrival time of the tide model is in Sumur of 19 minutes. which is slightly different from previous studies due to different modeling applications and different initial tide locations. The highest tsunami run-up of the coastal model is in Lesung and Sumur of 2.5 meters height which almost matches the results of field observations.

1 Introduction

The Indo-Australian plate meeting with the Eurasian plate in the south of Java is almost perpendicular [1]. Therefore, in the south of Java, shallow tectonic earthquakes often occur. Based on the tsunami catalog from 1600 to 2021 from the National Oceanic & Atmospheric Administration (ngdc.noaa.gov), 205 earthquake-generated tsunami data were obtained and 27 tsunamis caused by volcanoes and underwater landslides. The eruption of Krakatau has caused tsunamis since 416, 1883, and 1928. The explosion on August 27, 1883 is one example of a large tsunami caused by the eruption that caused a tsunami as high as 30 meters in the Sunda Strait, killing around 36,000 people (geonet.org.nz).

Before 1883, the young Mount Krakatau complex was formed which consisted of three cones of the Krakatoa volcano. The northernmost one was called Poeboewetan (now called Sertung Island), the southernmost was called Rakata, and in the middle was Panjang Island [2]. A new volcano known as Mount Anak Krakatau emerged from the ancient caldera area in 1927 (vansandic.com). Anak Krakatau is an active volcano with a growth rate of 0.5 meters (20 inches) per month. The eruption of Mount Anak Krakatau which occurred on December 22, 2018, generated a tsunami in the Sunda Strait that impacted the coastal areas of Banten and Lampung. The number of victims who died due to the Sunda Strait tsunami was updated on February 15, 2019 was 437 people (bnpb.go.id). In addition, 31.485 people were injured, 10 were missing, and 16.198 people were displaced. (geologi.esdm.go.id).

The population of Banten in 2019 is 12,927,316 people. (bps.go.id). Banten's economic growth in 2022 is in the range of 5% - 6%. (bi.go.id). One of the suppliers of Banten's economy is the big company PT Krakatau Steel with a land area of 280 hectares with a net income of IDR 17.9 trillion (cilegonhills.id). From 2014 to 2018, the Central Statistics Agency (BPS) recorded domestic tourists coming to Anyer Beach, Carita, Tanjung Lesung and its surroundings reaching more than 81 million visits.

According to the Ministry of Energy and Mineral Resources, ESDM, Mount Anak Krakatau is located at coordinates of 6.10161° South and 105.42286° East (vsi.esdm.go.id). JAXA captured significant topographic changes in the southern island of Anak Krakatau and showed the difference between the state of the original morphology of the mountain wall in before and after the Krakatau eruption in 2018 (eorc.jaxa.jp). Heidarzadeh [3] calculated the area of landslide material due to the eruption of Anak Krakatau There was a mass loss with a height of 228 m. The length of the avalanche from the mountain mass is estimated to be 1.5 to 2.5 km long and the tsunami amplitude at the source as high as 100 meter to 150 m. Tsunami recorded flow depth of 2 to 4 meter on the southern coast of Lampung, and depth of 0.5-7 meter on the western coasts of Banten [4]. The worst affected areas are around Carita Beach, Tanjung Lesung and Sumur with a run-up height of 7 to 13.5 m.

Research on tsunamis caused by non-seismic sources is absolutely necessary to minimize the impact on human

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and material losses. The method is to remodel past events according to actual events so that the mechanism and impact of the damage is known in order to anticipate the future with a worse return scenario.

2 Tsunami characteristics

Tsunami is a large wave that occurs when parts of the ocean floor change due to plate movements, volcanic eruptions, or underwater landslides [5]. Tsunami waves can reach tens or even hundreds of meters in height. The wave period is between 10-60 minutes with a wavelength of 50-200 km (ngdc.noaa.gov). Based on the number of tsunami-causing events caused by earthquakes (earthquake): 75%, submarine landslides (9%), volcanic activity (volcanogenic tsunami), 8%, meteorology (risaga) 2%, and unknown sources such as impact meteorites as much as 6% [6]. Tsunamis from volcanic eruptions occur when some of the energy released during an eruption is transmitted to the sea, generating impulsive waves by the displacement of the water.

Hydrodynamics discusses governing equations and numerical methods for tsunami modeling. In shallow water conditions, water particles have no vertical acceleration and the water pressure is the same as the pressure due to gravity. In other words, the movement of mass and energy at shallow depths becomes the same in all spaces [7]. Spherical and Cartesian coordinate equations are formulated as follows:

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

$$\frac{\partial P}{\partial t} + \frac{gh}{Rcos\varphi}\frac{\partial \eta}{\partial \psi} - fQ = 0 \quad (2)$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \varphi} - fQ = 0 \quad (3)$$

where n is the elevation of the water surface; (P, Q) shows the volume flux of the fluid material in the X (West-East) and Y (South-North) directions; (ϕ,y) denotes Earth's latitude and longitude; P = h u and Q = h v; R is the radius of the Earth; g is the acceleration due to gravity and h is the depth of the water. Equation (1) can reflect the sources of underwater tsunamis and landslides. The W is the planet's rotation for Coriolis forces, and φ (phi) is the azimuth angle. Therefore, the shallow water equation in Cartesian coordinates can be used as a reference as follows:

$$\frac{\partial \eta}{\partial t} + \left\{\frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y}\right\} = -\frac{\partial h}{\partial t} \quad (4)$$

$$\frac{\partial P}{\partial t} + gh\frac{\partial \eta}{\partial x} - fQ = 0 \quad (5)$$

$$\frac{\partial Q}{\partial t} + gh\frac{\partial \eta}{\partial yt} + fP = 0 \quad (6)$$

The following nonlinear shallow water equation is implemented in Spherical Coordinates as follows:

$$\frac{\partial \eta}{\partial t} + \frac{1}{Rcos\varphi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}(\cos\varphi Q)\right\} = -\frac{\partial h}{\partial t} \quad (7)$$

The landslide area has a grid dimension of nx and ny where nx and ny stand for the total number of grids in X and Y direction, respectively, and in total, nt snapshots are created to trace the variation of seafloor position in time, the variation of seafloor can be represented as,

$$\frac{\partial P}{\partial t} + \frac{1}{Rcos\varphi}\frac{\partial}{\partial \varphi}\left\{\frac{P^2}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \varphi}\left\{\frac{PQ}{H}\right\} + \frac{gh}{Rcos\varphi}\frac{\partial \eta}{\partial \psi} - fQ + F_x = 0 \quad (8)$$

$$\frac{\partial Q}{\partial t} + \frac{1}{Rcos\varphi}\frac{\partial}{\partial \varphi}\left\{\frac{PQ}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \varphi}\left\{\frac{Q^2}{H}\right\} + \frac{gH}{R}\frac{\partial \eta}{\partial \psi} + fP + F_y = 0 \quad (9)$$

where H is the total water depth and H = n + h; n is the elevation of the water surface; h is the water depth; and Fx and Fy represent the downward frictional forces in the X and Y directions, respectively.

$$\Delta h(i,j,k) = h(i,j,k) - h0(i,j) \quad (10)$$

in which *h(i, j, k)* denotes the instantaneous water depth at (*i, j*) at time level k and *h0(i, j)* represents the original position of on the seafloor.

3 COMCOT Model

Tsunami modeling based on numerical calculations is quite useful for explaining and providing scientific solutions to various technical problems in tsunami mitigation efforts. The arrival time of tsunami after deformation, provides an opportunity for mitigation policies. The COrnell Multi-grid COupled Tsunami (COMCOT) application is a numerical model based on the Shallow Water Equations (SWE) [7]. The performance of the numerical model based on SWE is superior because it fulfills technical requirements such as: hydrodynamics, alignment of actual applied cases, operating conditions of work and scientific evaluation. COMCOT has similarities with TUNAMI starting from the model structure, numerical scheme, programming language, application of Manning roughness [8].

The tsunami modeling focuses on the vicinity of Banten with coordinate boundaries 104° - 106° East, and 5.7° - 6.8° South with the nested grid arrangement with five layers. Bathymetric and topographic data of use with the GEBCO bathymetry for a wider scope with a resolution of 463 meter (gebco.net) as the first and the second layer data. From the first to the third layers, National Bathymetry Data (BATNAS) is formed from the inversion of gravity anomaly data resulting from altimetric data processing and bathymetry survey data carried out by national institutions. The supporting layer is National Digital Elevation Model (DEMNAS) that built from several data sources including IFSAR data (5 meter resolution), TERRASAR-X (5 meter resolution) and ALOS PALSAR (11.25 meter resolution), by adding the stereo-plotting of mass point. The spatial resolution of DEMNAS is 0.27 arc-second (tanahairindonesia.go.id).
In this study, the process of integrating BATNAS and DEMNAS data was carried out to obtain higher resolution results to be used as a third layer. This process is able to change the value of 0.003633 degree to 0.0004488 degree. This means that the general and rough bathymetric depth of 403.6 meters has been changed to a more detailed and refined depth of 49.8 meters. For more details, see Table 1.

Table 1. Resolution of grid size layer.

Lyr	Data ref.	Area	Res (degree)	Res (meter)
1	BATNAS	Province	0.003633	403.6
2	BATNAS	Regency	0.003633	403.6
3	BATNAS & DEMNAS integration	Village	0.0004488	49.8

4 Source dimension

We used the flank collapse scenario [3] of COMCOT to make a simulation of Mount Anak Krakatau. Flank collapse is the initial basis for the movement of landslides from the mountain cliffs towards the coast, causing sea deformation. The model outputs area a map of the maximum tsunami source from the tsunami source to the affected area; detailed map of affected area; snapshots propagation maps with time sequences; the estimated tsunami arrival time in the affected area; a map of the extent of the landslide that caused the tsunami; distribution map of the distribution of real and initial tide gauges; and tsunami or marigram signals in the affected area.

We took references about the shape, size, and estimated direction of the flank collapse avalanches based on satellite data of Japan satellites. JAXA captured a comparison of the two HH amplitude images acquired before (August 20, 2018) and after (December 24, 2018) the eruption. The white-dotted circle shows Anak Krakatau Island (eorc.jaxa.jp). A Japanese website reported that the height of the mountain dropped from 338 meters to 110 meters length of the tsunami source, respectively. Then the collapse wall of the mountain generated a deformation wave to the seaward. To analyze the extreme conditions of the potential tsunami, the landslide volume referred to Haidarzadeh [3] stated that the volcano lost 228 meters of its top structure to the sea due to the eruption. An overview of the dimensions of the landslide of Mount Anak Krakatau in horizontal (JAXA) and vertical form in Figure 1. CCTV camera of observation office of Mount Anak Krakatau in Pasauran, Cinangka, Banten showed that Mount Anak Krakatau reduced the peak height to 110 meters that is lower than Sertung island (183 m) and Panjang island (132 m) (esdm.go.id), see Figure 2.

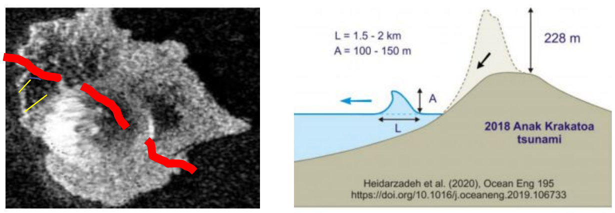

Fig. 1. (Left) Dimensions of the landslide of Mount Anak Krakatau in horizontal (JAXA). (Right) Vertical cartoon show crater collapsed dimension [3].

Fig. 2. CCTV camera of observation office in Pasauran, Cinangka, Banten shows before (top) and after (bottom) eruption of Mount Anak Krakatau (esdm.go.id).

In this study, we determined Mount Anak Krakatau landslide dimensions of 2000 meters long, 1500 meters wide, and 228 meters thick or conversion of landslide space volume of 0.4 km3. We use a maximum slope of 40 degrees. The direction of the landslide starts from the location of Mount Anak Krakatau to the southwest with coordinates 6.101° South and 105.419° East to 6.121° South and 105.408° East. Landslides are always described as a polygon plane. The slope of a landslide flow is described as a length which is usually wider than the dimensions of the width. This type is called rotational slide or flow slide. Meanwhile, if the length of the slide does not exceed its width, it is called a wide slide. This incident usually occurs in ditches, river banks and hillsides [9]. This second scheme is quite appropriate in describing the landslide of Mount Anak Krakatau due to the flank collapse of the mountain eruption. The dimension of the Mount Anak Krakatau landslide scenario from flank collapse can be seen in Figure 3.

5 Results

The focus locations of the potential tsunami-affected locations in the future are crossing centers as connections between large islands, industrial centers, tourist centers and densely populated settlements. The height and arrival time of the tsunami were recorded at artificial tides located on the seashore with depths below 100 meters. Seashore generally still characterizes the open sea with the character of linear wave propagation. Seashore is an area on the edge of the water that is affected by tides' highest and lowest ebb. Beach border is land along the edge whose width is in accordance with the shape and conditions of the physical beach, at least 100 meters from the highest tide point towards the mainland [10].

For the purposes of a tsunami early warning, the calculation estimate for the earliest initial arrival time and tsunami height uses the seashore area. The resolution of coastal bathymetry is not really necessary because it is more concerned with the speed of tsunami early information with a wide map scale. The product of warning information contains the coarse map of hazard scenario, evacuation time, and tsunami risk. The information is available at a map scale of 1:100 000 [11].

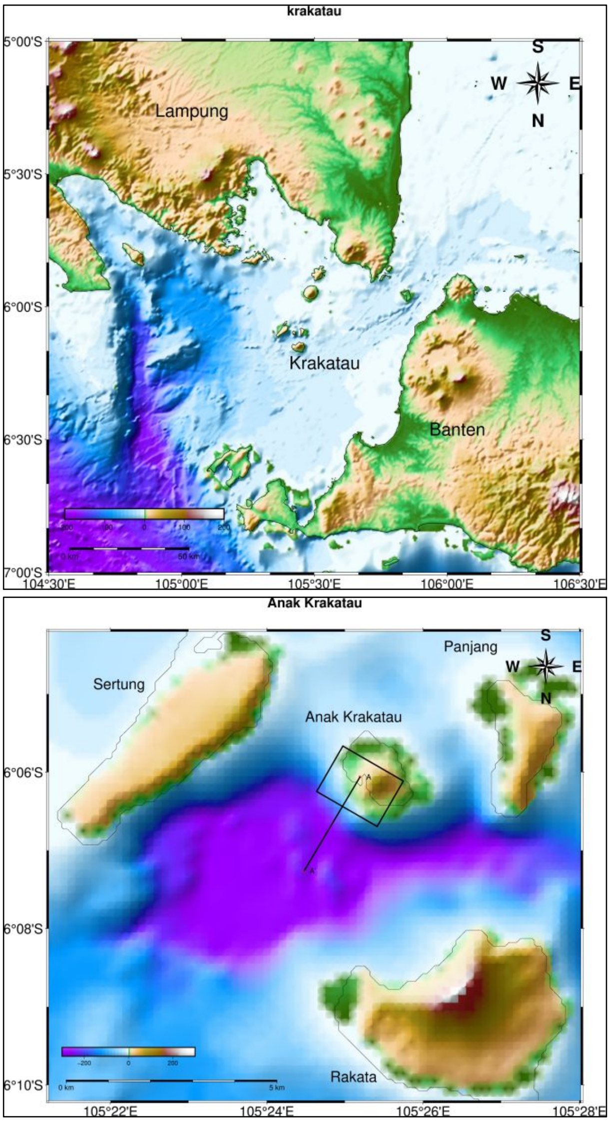

Fig. 3. (Top) Location of Mount Anak Krakatau in Sunda Strait between Banten and Lampung. (Bottom) Dimension of the Mount Anak Krakatau landslide from flank collapse. Direction of the landslide is denoted with A-A'.

Ploting tidal points on the mainland would result in overlapping signals on the tide gauge, rendering the modelling process unsuccessful. Therefore, artificial stations were strategically positioned on the deep sea. These stations measure the height and arrival time of the tsunami at those specific locations, providing valuable data before landfall [8]. The position of artificial tides on the seashore can be seen overall in Figure 4 is denoted by a yellow circle.These images depict the tsunami model in the first layer with wide bathymetry and still coarse resolution using GEBCO.

Tsunami simulation of the initial tide gauge show the results in Banten province precisely in Ciwandan, Anyer, Jambu, Carita, Labuan, Lesung, dan Sumur. Tsunami height and first arrival time in the seashore of Ciwandan as the farthest coast shows 0.45 meter height and 37 minutes. Anyer gives 0.7 meter height and 25 minutes. Jambu or Marina gives 1.4 meter height and 28 minutes. Carita showed the highest run-up of 1.8 meter height and 33 minutes. Labuhan shows 1.1 meter height and 34 minutes. Lesung shows 1.5 meter height and 25 minutes as the fastest arrival time. Sumur is 1.3 meters high and 33 minutes. The Combination chart of tsunami simulation for initial tide gauge in seashore can be seen in **Figure 5**.

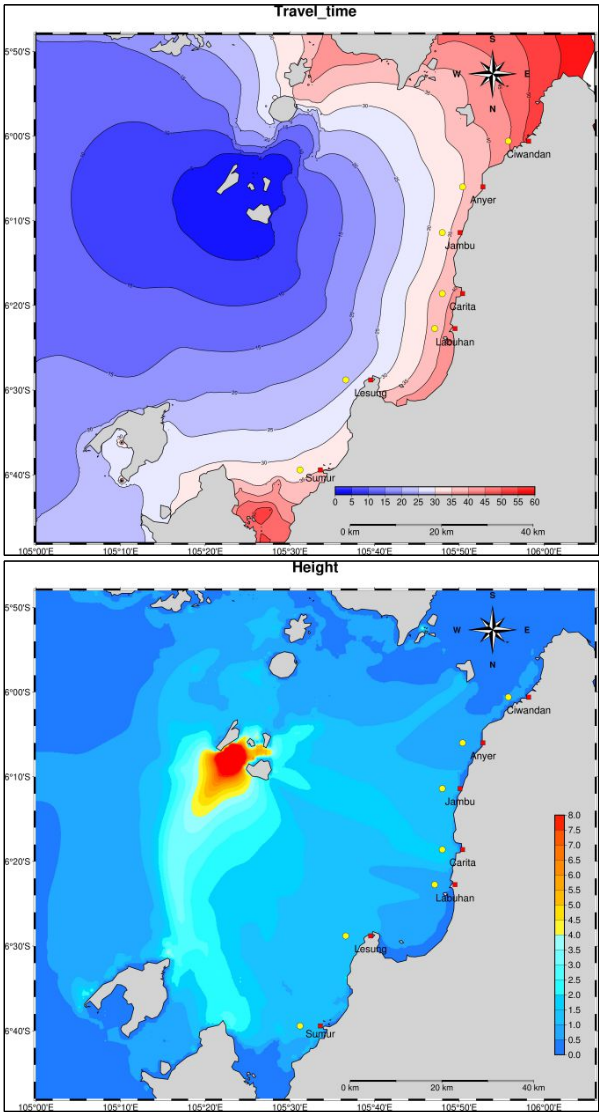

Fig. 4. (Top) Tsunami travel time from the source of Mount Anak Krakatau. (Bottom) The tsunami height reached the coastal area of Banten. Yellow circle denotes the initial tide and the red box shows the observation tide.

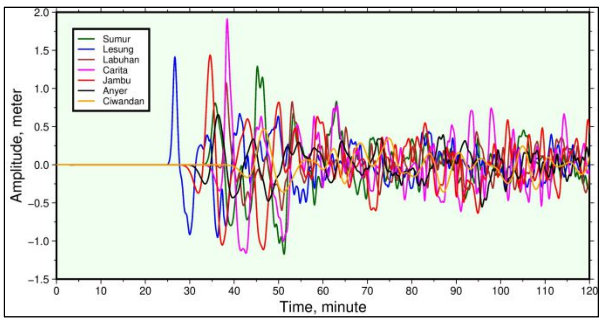

Fig. 5. The charts of height and arrival time of tsunami simulation from top to bottom for initial tide gauge of Lesung, Sumur, Labuhan, Carita, Jambu, Anyer, and Ciwandan.

Artificial tides occur in the deep ocean. Field measurements of tsunamis are carried out in the field because they measure traces of tsunami waves and inundation in land. To confirm the observation results, the inundation values from the tsunami model results are needed by matching the coordinates of the model adjacent to the tide gauge observation location and field measurements [12, 13]. This study shows detailed results that are observed using the last layer with integration of bathymetry and topography so as to get better resolution results even though the amplitude and arrival time values are different from the first and second layer. Table 1 show that the third layer is used as a reference to describe the actual model output. As shown in Figure 6, respectively it describes the area of (1) Ciwandan, Anyer, Jambu, (2) Carita and Labuhan, (3) Lesung Peninsula and Sumur. As a comparison, the model data taken must be based on the location of the coast or land where the coordinates of the location coincide with measurements in the field or other research.

Ciwandan beach close to Cilegon represents the national industry of chemical, steel and oil sectors. Ciwandan has the coordinates 6.050169° South, 105.91878° East. The Ciwandan coastal model show result of tsunami height of 0.5 meters almost the same as tide model that gives 0.5 meters height. The tsunami arrival time of 33 minutes is different with other study [14] that gave of 1.4 meters height and time of 38 minutes. Previous study used a spatial resolution of 200 m for the simulations of tsunami propagation over the entire Sunda Strait area using a combination of GEBCO and DEM data. Whereas this study uses a resolution of 49.8 meterss for the potential affected area of Ciwandan to Anyer. Near Ciwandan is Anyer beach as a famous tourist area with elevation of 50 meters above sea level and followed by the highway that extends along the beach [15]. Anyer has coordinates 6.1214° South, 105.8613° East. The coastal model has nearly same value with tide model of 0.6 meters height but different with previous study because of distinct resolution data. Jambu coastal model with coordinate 6.1896° South, 105.8346° East, showed a maximum tsunami height of 1.0 meters and matches to the tide gauge measurement of BIG at Jambu which shows an amplitude of 0.9 meters. The tide model arrival time of 27 minutes is still relevant with tide measurement of 29 minutes [16]. This models are litle bit different with previous study which has 1.4 meters height and 38 minutes. The Jambu model is higher than the field survey observations that based on a flow depth of 0.8 m [4]. The tsunami height around Ciwandan, Anyer, and Jambu are low because the direction is oposite to the propagation of the tsunami wave and has long distance to the tsunami source

Carita beach is located in the coordinates 6.31062° South, 105.83917° East has a bay morphology so that the tsunami height is amplified into 2 meter height. The tsunami propagation was emitted perpendicularly from the source radiating through the narrow gap on Rakata Island and Panjang island. The coast is in accordance with a field survey of 1.7 meters. Meanwhile, the arrival time of the tsunami was nearly the same as the results of Giatchelli [14] for 37 minutes. The entire bay area experienced a resonant oscillation event which resulted in a high energy amplification, larger amplitude and extended period of tsunami waves. As happened in Hangzhou Bay, China when it felt the 2011 Tohoku, Japan Tsunami, which experienced high energy amplification and a long oscillation duration in the bay [17].

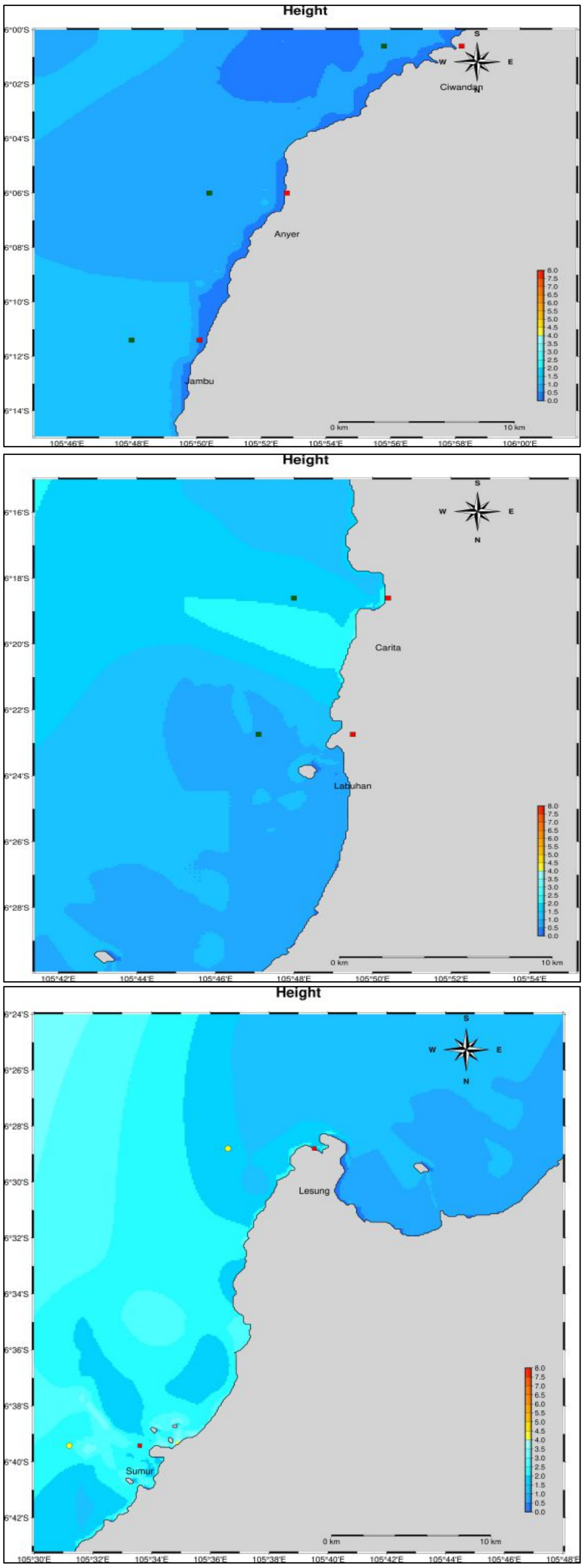

Fig. 6. Tsunami inundation reached (Top) Ciwandan, Anyer and Jambu area, (Midle) Labuhan and Carita, (Bottom) Lesung peninsula and Sumur. Data taken from integration of BATNAS and DEMNAS. Yellow dot denotes initial tide and red box shows coastal tide model.

The Labuhan beach is prone to disasters because it is a sub-district with the highest population density compared to other sub-districts, namely 3,574.71 people per square kilometer (BPS). Labuhan was built as a power station with 600 MW units and began in 2007 with an initial investment of $492,940,279 (PLN). The Labuhan coastal model with the coordinates 6.37851° South, 105.81933° East, showed a maximum tsunami height of 1.5 meter that was different from the previous study.

Table 2. Comparison to previous study. Tsunami height (H, meters), Time difference (T, minutes), n.a (no annotation). Field survey measurement is from Muhari [4]. Other model from Giachetti [14]. This study contains tide model (yellow) and coastal model (red). The model numbers are (1) Ciwandan, (2) Anyer, (3) Jambu, (4) Carita, (5) Labuhan, (6) Lesung, and (7) Sumur.

No	*Muhari et al (2019)*		Tide model (yellow)			Coastal mode (red)		*Giachetti et al (2012)*	
	Long, lat	*H*	Coord	H	T	Long,, lat	H	*H*	*T*
1	*n.a*	*n.a*	105.930, -6.010	**0.5**	**33**	105.970, -6.010	**0.5**	*1.4*	*38*
2	*n.a*	*n.a*	105.840, -6.100	**0.6**	**28**	105.880, -6.100	**0.5**	*1.5*	*42*
3	*105.8469 -6.17453*	*0.8*	105.800, -6.190	**1.4**	**27**	105.835, -6.190	**1.0**	*1.4*	*38*
4	*105.8409, -6.3113*	*1.7*	105.800, -6.310	**1.9**	**30**	105.840, -6.310	**2.0**	*2.9*	*37*
5	*105.8215, -6.3788*	*1.2*	105.785, -6.379	**1.0**	**31**	105.825, -6.379	**1.5**	*3.4*	*40*
6	*105.6581, - 6.4799*	*3.1*	105.610, -6.480	**1.4**	**25**	105.659, -6.480	**2.5**	*3.0*	*30*
7	*105.6166, - 6.5677*	*1.2*	105.520, -6.657	**0.8**	**19**	105.560, -6.657	**2.5**	*3.0*	*30*

6 Discussions

The difference in these results is understandable due to data source, observation location, and the modeling application being run. Previous researchers [3] used GEBCO 2014 global data that had been interpolated to produce a resolution of 8 arc second (about 250 m). In general, this model is larger than field surveys that rely on flow depth on land [4]. The initial tide gauge is placed at a depth of less than 10 meter which matches the previous model with a bathymetry depth of 5 meter to 13 meter [14]. This study uses run-up simulation calculations by adding a high resolution of bathymetry and topography by using assimilated national data from BATNAS and DEMNAS with a resolution of 49 meters. Therefore, the results of this study can be claimed to be more valid and up-to-date. Other researchers have obtained tsunami height data from flow depth traces in the field a few days after the 2018 Mount Anak Krakatau tsunami incident. This research uses purely the model results in the form of the maximum tsunami height. This research modeling application uses COMCOT version 1.7, the same as the previous research.

7 Conclusions

A volcanic eruption occurred in 2018 with a flank collapse type that then triggered an avalanche that reached the seabed, causing deformation of the volume of seawater. The impact of the tsunami accumulated around Banten and Lampung Provinces. The treatment of integrating topographic and bathymetric data to produce high resolution has quite an impact on the quality of tsunami height and inundation distance values, as has been done by previous researchers who combined ASTER, DISHIDROS, GEBCO and DEMNAS data from year 1995 to 2012. Meanwhile, this study combines BATNAS and DEMNAS as latest data. The tsunami model consists of the initial tide model and the coastal model.

The tide model with initial depth to show the propagation of tsunami waves reaching the coastline. Tide model was placed in 10 meter depth that showed tsunami heights ranged from 0.5 meter to 1.9 meter. To approach the results of field observations, the coastal model was placed at a very shallow depth close to land. Comparisons with other previous modeling studies did not find common ground because the applications used were different, namely VolcFlow [18] which specifically simulates lava flow during the flank collapse of Mount Anak Krakatau and the resolution used 200 meter [14]. Even though the initial tide depth is almost the same with the previous study. Meanwhile, this study uses COMCOT which only requires the polygon area and the thickness of the landslide layer. The highest tsunami run-up of the tide model is in Carita of 1.9 meter height. The fastest arrival time of the tide model is in Sumur of 19 minutes.

To adapt to field observations and surveys, the coastal points were placed on land or close to the coast. The resulting tsunami height from the coastal model is higher than the tide model because it is approaching the coast where the slope increases the tsunami height. The results ranged between 0.5 meter to 2.5 meter quite similar to field results and actual instrument measurements. The highest tsunami run-up of the coastal model is in Lesung and Sumur of 2.5 meter height.

8 Recommendations

This research can be used to build awareness and preparedness for tsunamis. The research results need to be continued to the socialization stage by placing the history, dangers, impacts and mitigation of disasters in public literature so that the level of community preparedness increases. We recommend integrating bathymetric and topographic data in each tsunami modeling to obtain detailed results. Apart from that, to obtain much better results, topographic and bathymetric field surveys are needed both in areas where the tsunami originates from volcanoes or landslides, as well as in every area that is potentially affected. Areas with very high resolution can be recommended as valid information for very detailed evacuation routes and refugee shelter locations according to disaster regulations. Mitigation efforts have become very effective and planned to anticipate similar disasters in the future. Apart from dampening waves, mangrove forests are also the first place where people seek shelter by climbing trees. Research shows that the denser the coastal forest, the higher the level of attenuation of tsunami waves, the weaker the current and hydraulic forces [19].

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