Landslide triggered tsunami modelling: A study in Anak Krakatoa collapse

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Abstract. The Anak Krakatoa volcano in Sunda Strait is a tsunami threat to the southern part of Sumatra Island and the west part of Java Island as the eruptions and landslides it generates may trigger a tsunami. As the coasts of West Java are densely populated areas, if a tsunami occurs, then the loss and casualties would be massive. Therefore, a hazard assessment in the area is necessary which includes a simulation of possible tsunami occurring in the region. We simulated the 2018 tsunami in Sunda Strait triggered by the collapse of the Anak Krakatoa flank using the landslide parameters inferred from previous studies simulating that the 2018 tsunami event. The water wave propagation in this simulation demonstrates a tsunami that travels rather fast, where the tsunami reaches the Panaitan Island in 20 minutes and has reached the mainland around 30 minutes. The simulated landslide created a water wave amplitude as high as 60 m in the nearby islands of Krakatoa Archipelago, down to less than 10 m in the mainland of Java Island. This result relatively correlates with the run-up height data measured in the field by previous studies in 2019 and 2020. The shape of the coastline also determines how the water waves affect the area, which should be an essential factor in the hazard assessment.

1 Introduction

The subduction zone alongside the west of Sumatra all the way to the south coast of Java had made the islands in those areas vulnerable to tsunamis, either caused by tectonic earthquakes, volcanic eruptions, or other causes of submarine landslides. The Krakatoa Archipelago, a volcanic island group in the Sunda Strait, threatens the adjacent islands including Java and Sumatra with the possible tsunami caused by its volcanic activities. The Krakatoa volcanic eruption on 26 August 1883 is recorded as the deadliest volcanic explosion creating a tsunami and causing at least 36000 death tolls [1]. The emerging of the Anak Krakatoa volcano after the eruption becomes another tsunami threat in the area. The collapse of the Anak Krakatoa volcano flank in 2018 had caused a landslide that triggers the latest tsunami in Sunda Strait, resulting in hundreds of fatalities.

Not far from the threatening volcano, the west coast of Java Island is a densely populated area and is well-known for its tourist resorts. As consequence, the area is not only vulnerable but also at a high risk of a tsunami with a possible immense number of losses and casualties. That being the case, the simulation of a possible landslide-triggered tsunami in the area is important as the information of arrival time and the estimated wave height would improve the early warning system and hazard assessment in the area. In terms of the hazard it poses to people, landslides and volcano flank collapse like in the case of Krakatoa represent an important tsunami source [2].

2 Geological setting

The Krakatoa volcanic complex is part of an NNE-SSW trending lineament of a quaternary volcanic edifice that lies approximately perpendicular to the Java Trench [3]. After the 1883 eruption of Krakatoa, which is one of the largest volcanic explosions in history, the northern portion of Krakatoa Island disappeared and was replaced by a caldera [4]. In 1928, Anak Krakatoa (the Child of Krakatoa) emerged on the submarine caldera formed during the 1883 eruption [5]. The caldera, together with three surrounding islands are remnants of the 1883 Krakatoa eruption, creating a complex called Krakatoa Archipelago. The archipelago consists of Anak Krakatoa Volcano, Sertung Island, Panjang Island, and Rakata Island (Fig. 1).

The cone of Anak Krakatoa was built up by the recurrent lava flows and pyroclastic fall deposits up to 350 m high before it collapses in 2018 [5]. Accompanied by a series of volcano eruptions from 22 to 26 December 2018, the collapse of the volcano flank generated a tsunami in Sunda Straits on 22 December 2018 [6]. The eruption started on 23 October 2007 with minor eruptions that created ash clouds and Plumes and continued with fluctuating eruptive activity until October 2018 when the volcano became more active with strombolian and explosive events. This eruptive phase continued for 175 days until 22 December 2018, when the activity suddenly evolved into a sector

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Fig. 1. The Anak Krakatoa volcano is a part of a volcanic island group (Krakatoa archipelago) along with Sertung Island, Panjang Island, and the remnants of Rakata cone of the old Krakatoa Island.

proposed that the collapse plane must extend below sea level to be able to drastically change the shape and volume of the island as observed from the photographs and radar images. He stated that the subaerial area of the island was estimated to be reduced by 49% due to the eruption.

The Anak Krakatoa flank collapse had been simulated in 2012, six years before the 2018 event, by Giachetti [9]. The study presents the simulation of the Anak Krakatoa landslide and tsunami propagation. The study infers that the highest wave amplitude is directed towards the southwest and that the presence of the Sertung and Rakata islands causes the wave height to be reduced in the northwest and southwest of the landslide scenario location.

3 Methodology

Numerical modeling is a fit approach to forecast wave propagation and inundation on land [10]. Different approaches of modeling have been presented for the 2018 Sunda Strait tsunami [8], [5]. In this research, we used a nonlinear Boussinesq equation in the wave propagation model provided by Geowave - a simulation software developed and managed in parts by Applied Engineering, Inc. The tsunami propagation model was performed to model water waves while accommodating the dispersive behavior of the wave during the generation, propagation [10], and inundation of tsunami waves [5]. Paris [5] compared shallow water simulation and Boussinesq simulation to assess the potential dispersive effects in Sunda Strait. His research shows that even though the first wave from both simulations is similar in the near field, there are dispersive effects in the far field where the period of the first water wave increases during the propagation. The Boussinesq model

does not constrain horizontal velocities to have a constant value wave model thus it could give us accurate vertical tsunami run-up and horizontal tsunami inundation in one simulation [11].

The bathymetric data of Krakatoa and Banten used in modeling was obtained from the DEMNAS (<http://tides.big.go.id/DEMNAS/index.html>), a part of the Indonesian Geospatial Information Agency owned by the government. It has a spatial resolution of 0.27-arcsecond, using vertical datum EGM2008. It was created from several sources including IFSAR (5m resolution), TERRASAR-X (5m resolution), and ALOS PALSAR (11.25m resolution).

The characteristics of a tsunami greatly depend on the source parameter, hence it is an essential factor in tsunami simulation. For a tsunami generated by subaqueous landslides, we need to be mindful of the volume, the dynamics of sliding masses, and water depth. The inadequacy in the information of landslide geometry is the challenging part of this modeling as it allows multiple possibilities of resulting models. We used parameters inferred from previous studies, including a landslide simulation by Paris [5] and a collapse scenario presented by Grilli [8]. The landslide simulation performed by Paris presented that the height of the Anak Krakatoa subaerial edifice was reduced from approximately 350 m before its collapse to about 120 m during its flank landslide which causes the 2018 tsunami in Sunda Strait. We defined the geometry of the landslide plane from a landslide simulation result performed by Paris [5] and a model of the Anak Krakatoa collapse scenario constructed from high-resolution satellite imagery and aerial photography by Grilli [8]. The slope is set to be 8° [10, 5] with the total estimated volume of our collapse model is about 0.18 km³ which is in between the estimation made by [5] and

Fig. 2. The landslide at the southwest rim of Anak Krakatoa triggered water waves traveling in the direction of the mass movement (a) with maximum wave height of almost 60 m at time 58 s (b) which decreases down to around 23.5 m less than 5 minutes after the trigger.

[8]. We assumed an initial depth of 25 m [8] and a density of 1500 kg/m³ [9].

Previous studies [5, 6, 12, 13] had provided field measurement data of inundation and run-up heights caused by the 2018 tsunami in Sunda Straits. In this study, we used two measurement data [6, 12] which we reckon would complement each other. The field measurement is mainly conducted in the Tanjung Lesung peninsula and around Marina Jambu where tsunami traces were identified. The observation suggests that Tanjung Lesung is the area with the highest run-up height along the coast of West Java in respect to the 2018 event tsunami.

4 Discussion

The debris avalanche of the landslide is directed to the southwest, thus displacing water in that direction and creating water waves as high as 60 m. In less than 1 minute, the first wave crest hit Rakata Island and Sertung Island in the southeast and the west of the landslide scar (**Fig(a)**). The wave with the highest amplitude travels in the same direction of mass movement and the opening between islands make it possible for the wave to go way through without a hitch. On the other hand, the presence of islands around the Anak Krakatoa volcano serves as barriers for the water which attenuates the wave traveling to the north and east of Anak Krakatoa (**Fig(b)**) wherein we see much lower amplitude.

The waves going to the southwest are the fastest to travel and Panaitan Island in the south became the first to be hit by the water wave. It might be associated with the bathymetry between Panaitan Island and the Krakatoa archipelago. The tsunami wavefront hit the island with a maximum amplitude of about 10.8 m, 20 minutes and 10 seconds after the landslide occurs (**Fig. 2(a)**). The crest of the leading wave then arrives at Tanjung Lesung beach in 5 minutes, having a water surface elevation of almost 10 m (**Fig. 2(b)**). Several minutes later, the waves enter Lada Bay with much lower wave of about only 2 m high. Directly after, at

1786 s after the trigger, the tsunami more than 13 m high hit Ujung Kulon, the most western part of Java Island (**Fig. 2(c)**). At 30 and a half minutes, the water waves reach Carita and Marina Jambu (**Fig. 2(d)**) with moderate wave height between 3 to 5 m and were followed by other parts of the mainland. The wave have gotten completely into the west coast of Java around 36 minutes after the landslide occurs.

The waves approaching the mainland, generally have lower amplitude and travel at a slower speed as a result of the shallower bathymetry. It is since a tsunami act as a shallow-water wave, where the traveling speed depends only on the depth of the ocean. Considering the landslide scar is oriented to the southwest, the wave is expected to have the highest crest in that direction. Therefore, we expect that the area in the southern part of the mainland would be subjected to higher water waves, which is consistent with our simulation.

We compare the arrival time of our simulation with the results from Grilli [9] and Paris [5] for two locations covered by those studies, Tanjung Lesung and Marina Jambu. From Table 1. It is noted that our tsunami simulation gives faster water wave propagation than two others but there is only 1-2 s difference. There is no recorded arrival time at Tanjung Lesung to be compared, but the data from Marina Jambu recorded the arrival time to be 33 minutes [5] which only differ one second compared to the simulation in this study. This signifies our simulation result, though more data to be compared is needed.

Table 1. The travel time of water waves computed in this study, compared with previous study

Computed	Travel time (s)		Location
	Giachetti et al. (2012)	Paris et al. (2019)	
26	28	29	Tanjung Lesung
32	33	34	Marina Jambu

Fig. 2. The water surface elevation of tsunami modeling (a) at time 1210 s (20 minutes) as the wave hit Panaitan Island with height of 10.8 m. (b) After about 5 minutes (at 1556 s), the wave first reaches the mainland at Tanjung Lesung beach with maximum height of almost 10 m.

Fig. 3. The run-up height measurement data at several sites obtained from field surveys conducted by Widiyanto [11] (green bullseyes) and Muhari [6] (red bullseyes)

A narrow bay such as the Lada Bay tends to amplify tsunami height, but both the simulation result and observation of run-up data in the field showed that the water wave here is not as high as expected, which we assume it was due to the presence of the Tanjung Lesung peninsula acting as a barrier for the Bay. As shown in **Fig. 3**, the run-up measurement from Widiyanto [12] recorded a low run-up height and scarce tsunami trace in this bay, meaning that the area is less affected by the 2018 tsunami. On the contrary, Tanjung Lesung peninsula had experienced such severe damage [6] with the highest run-up height measured in the research area. Based on field observation by Muhari [6], the run-up height in the peninsula is between 7 – 13.5 m with an average height of 10.6 m, while the highest run-up measured by Widiyanto [12] at the west coast of Tanjung Lesung gives 9.2 m. These field data agree with our simulation result whose water height is as high as 10 m in Tanjung Lesung but only 2 m at Lada Bay. The observation data of run-up heights around Marina and Carita are between 3-5 m, which is also very similar to our results. The comparison we mentioned might only be done at sites where the tsunami traces can be observed and measured. However, as the measured run-up values at most area are in agreement with the water

waves height of our simulation, we could also assume that the expected tsunami water height and arrival time at other places would conform with our result as well as. That being said, we could later use the simulation result and its parameter to aid in the work of tsunami hazard assessment and evacuation plan.

Both the run-up height observation and wave simulation suggest that Tanjung Lesung peninsula and Ujung Kulon are likely to be heavily affected by a tsunami. The fact that Tanjung Lesung is one of the tourist destinations in the region, become alarming as it is often packed with tourists. In the 2018 tsunami, the area is severely damaged, including the forest and beach areas. Further work is needed to determine the area with high risks, as the height if water wave does not always directly related to run-up height and inundation distance.

5 Conclusion

The landslide scenario in this research produces water waves as high as 60 m soon after the landslide, with the highest wave traveling to the south, echoing the direction of the debris movement. The water wave direction is, indeed, bound by the orientation of the landslide plane and also the presence of barriers, in this case, are the islands surrounding Anak Krakatoa. After coming out of the Krakatoa complex, the water wave travels radially in all directions. The highest wave crest, however, is aiming to the south to the Panaitan Island. The first wave then hit this Island with a height of more than 10 m.

In the mainland, the area first hit by the wave is the Tanjung Lesung peninsula, then followed by Ujung Kulon and the other area in the west coast of Java in the north of Tanjung Lesung. Tanjung Peninsula and Ujung Kulon both are hit by average height of 10 m water waves, the highest among other parts of the coast. Both areas have relatively deeper bathymetry than Marina Jambu or Carita Beach in the north, whose wave amplitude is much lower, which might contribute to the the height of water wave. The run-up measurement in the field conducted by Muhari [6] and Widiyanto [11] also show very similar pattern and are in agreement with each other, though the exact value of water wave and run-up height might not be comparable. That being the case, our simulation result is in agreement with the run-up record measured based on the tsunami traces in the field. However, we need to analyze further into the inundation record as the wave energy might be converted into run-up height or inundation distance depending on the topography/bathymetry of the coastlines.

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