



Field Survey of Tsunami Heights and Runups Following the 22 December 2018 Anak Krakatau Volcano Tsunami, Indonesia

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Abstract—The 22 December 2018 Anak Krakatau tsunami in Indonesia was a rare event in that few instrumental records existed of tsunamis generated by volcanic sources before this event. The tsunami, which left a death toll of 437, is of global importance as it provides opportunities to develop knowledge on generation, propagation and coastal effects of volcanic tsunamis. Here, we report results of field surveys along the coast of the Sunda Strait, Indonesia to study tsunami wave heights and coastal damage. We surveyed 29 locations and measured ranges of tsunami runup from 0.9 to 5.2 m, tsunami heights from 1.4 to 6.3 m, flow depths from 0.2 m to 3.0 m and inundation distances from 18 to 212 m. The largest tsunami heights and concentration of damage and fatalities occurred on the western shore of Java from Tanjung Lesung to Sumur. The largest cluster of fatalities occurred at Tanjung Lesung, where more than 50 people died while attending an outdoor music being held at the shoreline. The tsunami runup and tsunami height in Tanjung Lesung were 4.0 and 2.9–3.8 m, respectively. We believe this tragedy could have been avoided if the event organizers were more aware of the hazard posed by the Anak Krakatau volcano, as it had been actively erupting for several months prior to the tsunami, and simply moved the concert stage 100 m inland. Many of the locations surveyed demonstrated a similar pattern where the majority of casualties and destruction occurred within 100 m of the coast; in several locations, lives were saved where buildings were located at least this distance inland. The significant damage and numerous deaths which occurred in Sumur, despite the moderate tsunami height of 2.3–2.5 m, can be attributed to the extremely low-lying coastal land there. Flow depth in Sumur was 0.9–2.0 m. During our field surveys, nearly one year after the event, we noted that some of the damaged buildings were being rebuilt in the same locations just 10–30 m from the shoreline. We question this practice since the new buildings could be at the same tsunami risk as those damaged in the 2018 event.

Keywords: Tsunami, Anak Krakatau Volcano, Sunda Strait, field surveys, tsunami simulations.

1. Introduction

The eruption of the Anak Krakatau Volcano (AKV) (Fig. 1a) on 22 December 2018 resulted in a deadly tsunami along the coast of Sunda Strait, Indonesia (Muhari et al., 2019; Putra et al., 2020). Approximately 228 m of the top part of the AKV slid into the sea as a result of the eruption (Fig. 1b). The 2018 Anak Krakatau Tsunami (AKT) reached a maximum runup of 13 m (Muhari et al. 2019) along the southern coast of the strait which caused significant damage (Fig. 1c) and a death toll of 437 people. Approximately 50 people were killed in Tanjung Lesung resort (Fig. 1a) while attending a music concert at the time of the tsunami arrival. A short video recording of the incident of the tsunami attack on this music concert became available on internet days after the event which was viewed millions of times (<https://www.youtube.com/watch?v=2ERXCR86GU4>). Based on the analysis of seismic records from nearby seismometers, the origin time of the eruption and tsunami was estimated to be 13:56 UTC on 22 December 2018 (Heidarzadeh et al. 2020a).

The December 2018 AKT was a unique event as there have been few instrumentally-recorded volcanic tsunamis worldwide in the past. Therefore, the knowledge about the generation and propagation of these types of tsunamis has been limited before the 2018 tsunami. In this context, the 2018 AKT provided an opportunity to extend our knowledge on volcanic tsunamis as this event was recorded by several instruments such as tide gauges and seismometers as well as additional information were provided through field survey reports. Muhari et al.

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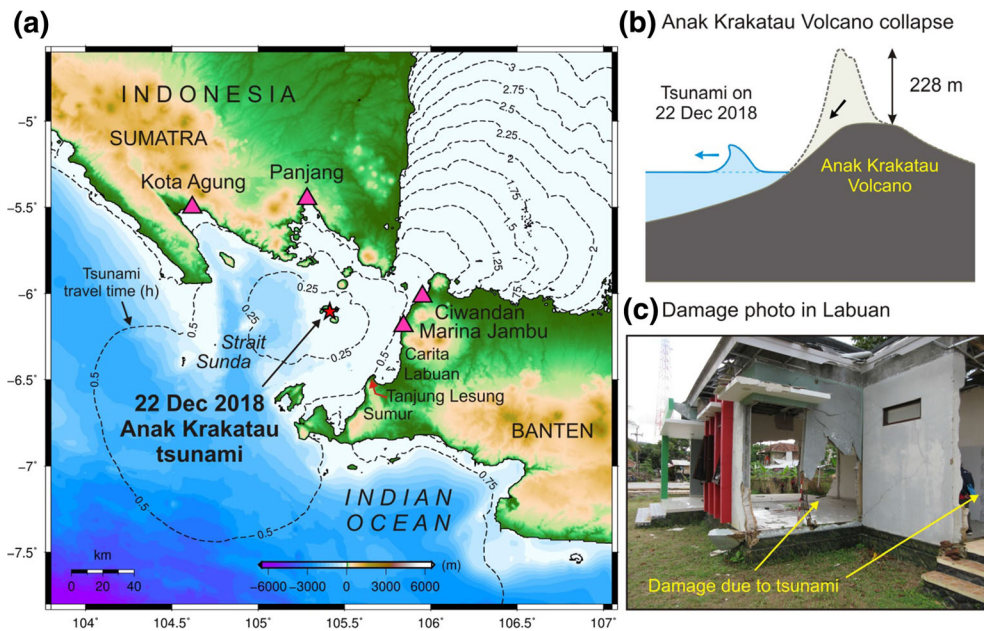


Figure 1

a The location of the 22 December 2018 Anak Krakatau volcano tsunami (red star) and the tide gauge stations (pink triangles). The dashed lines are tsunami travel times (TTT) in hours, with 15-min intervals, calculated using the TTT package by <http://www.geoware-online.com/>. **b** Sketch showing the collapse of the Anak Krakatau Volcano in 22 December 2018 where the top 228 m of the volcano collapsed into the sea; modified from Heidarzadeh et al. (2020a). **c** Illustration of damage made by the 22 December 2018 Anak Krakatau volcano tsunami in Labuan from the field surveys of this research

(2019) conducted field surveys of the northern and southern coasts of the Sunda Strait and reported maximum runup and flow depth of 13 m and 5.4 m, respectively. The field surveys by Putra et al. (2020) resulted in maximum runup, flow depth and inundation distance of 12.8 m, 3.6 m and 260 m, respectively. Tsunami sediment transport along normal transects to the shoreline also was studied by Putra et al. (2020) revealing that the sediment transport pattern appeared to be similar to that of earthquake-generated tsunamis. Heidarzadeh et al. (2020a) analyzed tide gauge records of the AKT and proposed a source model for this unique tsunami by applying numerical simulations; the source model proposed by Heidarzadeh et al. (2020a) consists of an initial pure-elevation wave with height of 100–150 m and length of 1.5–2.0 km. The numerical modeling of the event by Paris et al. (2020) and Zengaffinen et al. (2020) further reconfirmed the source model initially proposed by Heidarzadeh et al. (2020a). The volume of the sliding mass during the AKT was estimated at 0.2–0.3 km³ by Ren et al. (2020) whereas

Heidarzadeh et al. (2020a) reported it in the range of 0.175–0.326 km³. The volume estimate by Grilli et al. (2019) is 0.22–0.30 km³.

In this research, we report the results of field surveys of the areas affected by the 2018 AKT along the southern coast of the Sunda Strait. The surveys were conducted in the time period of 4–11 January 2020, approximately one year after the event. The objectives of the surveys were recording the tsunami heights and runup as well as flow depths. Although there have been at least two published reports of the field surveys before this study (i.e. Muhari et al. 2019; Putra et al. 2020), further field works of this kind are helpful to better understand the event and to provide complementary field data.

2. Data and Methods

A joint survey team including researchers from Brunel University London (UK) and Indonesian Institute of Sciences (LIPI) was formed to investigate

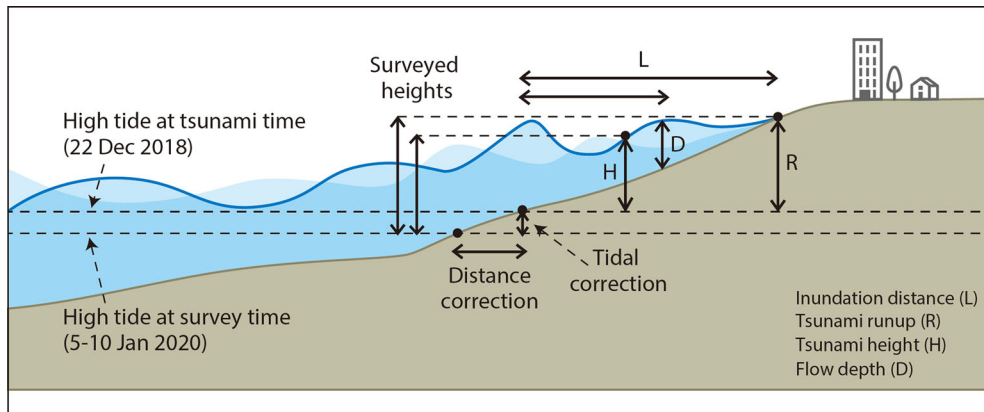


Figure 2

Sketch showing the method applied for surveys of tsunami heights and tidal corrections on the measured tsunami heights, tsunami runups and inundation distances in order to obtain actual heights and inundations

the areas affected by the 2018 AKT. The team visited the area in the period 4–11 January 2020. The surveyed locations were the southern coast of the Sunda Strait along the coastline from Ciwandan to Ujung Kulon National Park (Figs. 1, 3). Regarding characteristics of tsunami waves along the coast, we measured four parameters: tsunami runup (R), which is the vertical distance between high tide level (HTL) and the elevation level at maximum point of tsunami inundation (Fig. 2); tsunami height (H) which is the vertical distance between high tide level and the point of measurement; tsunami flow depth (D) which is the depth of the water above the ground at the point of measurement; and tsunami inundation distance (L) which is the horizontal distance between the coastline at HTL and the point of measurement (Fig. 2) (e.g. Synolakis and Okal 2005; Fritz et al. 2006; Satake et al. 2020). All measurements were made based on the HTL at the time of the survey (i.e. January 2020) and then were corrected relative to the HTL at the time of the tsunami (i.e. 22 December 2018) (Fig. 2) (e.g. Tsuji et al. 2011; Heidarzadeh et al. 2018, 2020b). Therefore, both heights and distances measured during the surveys were corrected. For tidal corrections, we benefited from tidal predictions provided by WorldTides (<https://www.worldtides.info/>). For distance corrections, an average beach slope of 0.05 was assumed. For example, given a height correction of 0.3 m due to tidal variations, the distance correction will be 6 m.

Height and distance measurements during the survey were made using a laser rangefinder of model TruPulse 200 manufactured by Laser Technologies (<http://www.lasertech.com>) assisted by a reflector and a Garmin GPS device (<http://www.garmin.com>). All measurement locations were georeferenced using the GPS device and were photographed. Details of the wave damage at each location were recorded. Although the surveys were conducted approximately one year after the event, tsunami watermarks existed in most of the locations; in particular inside the abandoned properties. Such locations, which demonstrated clear watermarks, were selected for tsunami height and distance measurements in this study. In addition, in most of the survey locations, we confirmed watermarks and inundation points by interviewing with local eyewitnesses. In our analyses throughout the article, we refer to death tolls at different locations along the Sunda Strait's coastline due to the AKT. These death tolls are solely based on our interviews with local eyewitnesses and do not represent official death tolls.

3. Hydrodynamic Analysis

The Sunda Strait region is a shallow water body with water depths less than 1000 m in most of its areas (Fig. 1a). In particular, the V-shaped estuary (also known as “ria”) coastlines to the north (i.e. around Panjang and Kota Agung) and most of the

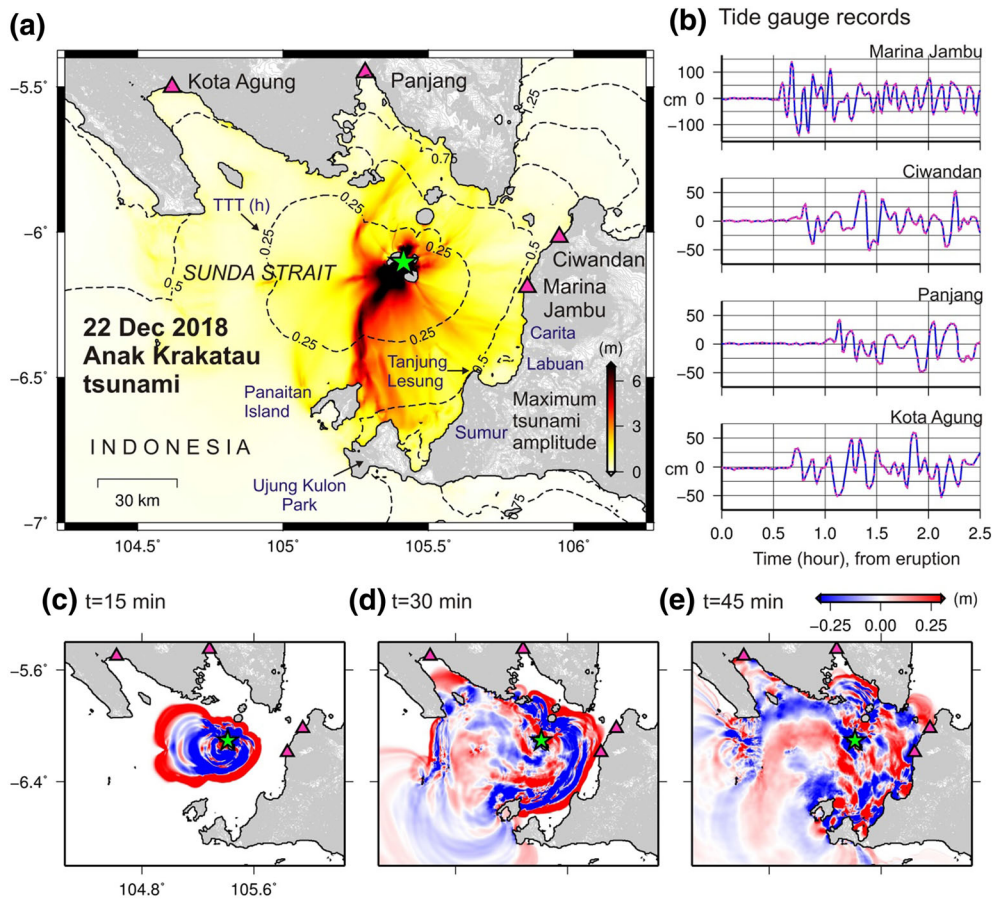


Figure 3

a Distribution of maximum tsunami amplitudes during entire tsunami simulations based on the tsunami model by Heidarzadeh et al. (2020a). The dashed lines are tsunami travel times (TTT) in hours with 15-min intervals. The star shows the Anak Krakatau Volcano which is the source of the tsunami. The triangles are the locations of tide gauge stations. **b** Tide gauge waveforms of the tsunami in various stations. The pink points on the tsunami waveforms are the data points while the blue lines connect these data points together. **c–e** Snapshots of tsunami propagation at different times

southern parts (i.e. Ciwandan, Marina Jambu, Carita, Sumur) have water depths of less than 500 m. Therefore, tsunami celerity (C), which is directly linked to water depth (d) with equation: $C = \sqrt{gd}$, where g is the gravitational acceleration ($g = 9.81 \text{ m/s}^2$), becomes relatively small in the Sunda Strait region. Due to the shallow bathymetry of the strait, seafloor friction plays a greater role than usual to dissipate tsunami energy (e.g. Satake and Heidarzadeh 2017; Heidarzadeh et al. 2016, 2017). Tsunami travel time (TTT) contours (Fig. 3a) and actual tide gauge records (Fig. 3b) reveal that it took 35–60 min for the AKT to arrive at the coasts. Tsunami source analysis conducted by Heidarzadeh et al.

(2020a), which was validated by actual tide gauge records of the AKT, resulted in a source model having 100–150 m initial wave height. In addition to the fact the aforesaid source model was validated by actual tide gauge records of the AKT, the other evidence for this source model comes from Borrero et al. (2020) who reported a runup of 85 m on the coast of a nearby island to the AKV, i.e. Rakata Island, which is located ~ 5 km to the south of the AKV.

Distribution of maximum simulated tsunami amplitudes (Fig. 3a) demonstrates that most of the tsunami energy was delivered towards the south coast of the Sunda Strait in the area to the south of Tanjung Lesung. The main tsunami energy beam is directed

Table 1

Results of field surveys of the 22 December 2018 Anak Krakatau Volcano tsunami listing locations of the survey points, row measurements, tidal corrections, tsunami runup (R), tsunami height (H), flow depth (D) and Inundation distance (L)

No.	Location	Lon. (°E)	Lat. (°S)	Row height (m)	Survey date and time (local time)	Tide correction (m)	R (m) ¹	H (m) ²	D (m) ³	L (m) ⁴
1	Sambolo-1	105.8821	- 6.0983	1.5	4 Jan 2020 (12:40)	0.0	N/A	1.5	N/A	N/A
2	Cilurah	105.8289	- 6.2563	1.6	7 Jan 2020 (09:50)	- 0.2	N/A	1.4	0.8	43
3	Pondok Paula	105.8260	- 6.2764	2.6	7 Jan 2020 (10:30)	- 0.2	N/A	2.4	0.7	49
4	Stefani Villa	105.8265	- 6.2820	3.3	7 Jan 2020 (11:05)	- 0.2	N/A	3.1	0.65	75
5	Carita-1	105.8295	- 6.3168	3.1	7 Jan 2020 (12:30)	- 0.2	N/A	2.9	1.7	23
6	Carita-2	105.8273	- 6.3333	3.2	10 Jan 2020 (10:00)	- 0.1	N/A	3.1	1.5	46
7	Labuan-1	105.8226	- 6.3713	1.6	7 Jan 2020 (14:35)	- 0.2	N/A	1.4	0.3	23
8	Labuan-2	105.8261	- 6.4205	1.1	7 Jan 2020 (15:30)	- 0.2	0.9	N/A	0.2	49
9	Tanjung Lesung-1	105.6532	- 6.4795	4.3	5 Jan 2020 (09:20)	- 0.3	4.0	N/A	N/A	109
10	Tanjung Lesung-2	105.6531	- 6.4802	4.1	5 Jan 2020 (09:00)	- 0.3	N/A	3.8	N/A	59
11	Tanjung Lesung-3	105.6531	- 6.4802	3.2	5 Jan 2020 (09:10)	- 0.3	N/A	2.9	0.9	24
12	Kasavana Beach Resort	105.6412	- 6.5047	6.5	8 Jan 2020 (16:05)	- 0.2	N/A	6.3	3.0	80
13	Joglo Beach House	105.6218	- 6.5527	4.2	8 Jan 2020 (14:30)	- 0.2	N/A	4.0	1.5	100
14	Banyuasih-1	105.6179	- 6.5675	5.4	8 Jan 2020 (10:30)	- 0.2	5.2	N/A	N/A	148
15	Banyuasih School	105.6166	- 6.5719	4.8	8 Jan 2020 (09:20)	- 0.2	4.6	N/A	N/A	96
16	Banyuasih-2	105.6248	- 6.5955	4.0	9 Jan 2020 (14:30)	- 0.1	N/A	3.9	2.5	94
17	Banyuasih-3	105.6248	- 6.5955	4.5	9 Jan 2020 (14:30)	- 0.1	N/A	4.4	3.0	94
18	Banyuasih-4	105.6208	- 6.5991	3.1	9 Jan 2020 (13:30)	- 0.1	N/A	3.0	1.0	100
19	Banyuasih-5	105.6086	- 6.6324	2.7	9 Jan 2020 (12:30)	- 0.1	N/A	2.6	N/A	98
20	Cisih Beach	105.5997	- 6.6471	2.3	5 Jan 2020 (16:00)	- 0.4	N/A	1.9	0.8	127
21	Sumur-1	105.5833	- 6.6564	2.8	5 Jan 2020 (13:30)	- 0.4	N/A	2.4	2.0	98
22	Sumur-2	105.5823	- 6.6568	2.8	5 Jan 2020 (11:20)	- 0.3	N/A	2.5	1.5	68
23	Sumur-3	105.5821	- 6.6575	2.8	5 Jan 2020 (10:55)	- 0.3	N/A	2.5	1.8	104
24	Sumur-4	105.5723	- 6.6789	2.9	5 Jan 2020 (12:40)	- 0.4	N/A	2.5	0.9	28
25	Sumur-5	105.5726	- 6.6800	2.7	5 Jan 2020 (12:00)	- 0.4	N/A	2.3	1.0	37
26	Kertamukti	105.5689	- 6.6841	3.0	9 Jan 2020 (11:30)	- 0.1	N/A	2.9	2.0	113
27	Ciputih Resort-1	105.5491	- 6.7018	4.0	9 Jan 2020 (10:30)	- 0.1	N/A	3.9	1.2	70
28	Ciputih Resort-2	105.5497	- 6.7018	4.1	9 Jan 2020 (10:30)	- 0.1	N/A	4.0	1.7	18
29	Sumur-6	105.5418	- 6.7048	3.1	9 Jan 2020 (09:30)	- 0.1	3.0	N/A	N/A	212

¹Tsunami runup (R)

²Tsunami height (H)

³Flow depth (D)

⁴Inundation distance (L)

towards Panaitan Island and the Ujung Kulon National Park (Fig. 3a); however, both locations are uninhabited. The pattern of maximum tsunami energy distribution inferred from Fig. 3a is consistent with map of most damage and death reported in the aftermath of the AKT in Tanjung Lesung and Sumur.

4. Tsunami Runup Field Surveys

In total, 29 coastal locations along the coast of the Sunda Strait were surveyed (Table 1; Fig. 4). Based on the survey results, the tsunami runup (R), tsunami

heights (H), flow depths (D) and inundation distances (L) vary in the ranges of 0.9–5.2 m, 1.4–6.3 m, 0.2–3.0 m and 18–212 m, respectively (Fig. 4). Clear tsunami watermarks were identified in most locations. It can be established from our results that largest tsunami heights and inundation distances were concentrated along the coastline to the south of Tanjung Lesung (Fig. 4) in line with the results of simulations which showed maximum tsunami energy was directed to this part of the coast (Fig. 3a). The maximum tsunami height in our survey (i.e. 6.3 m) belongs to Kasavana Beach Resort located south of Tanjung Lesung (Fig. 4) where flow depth was 3.0 m

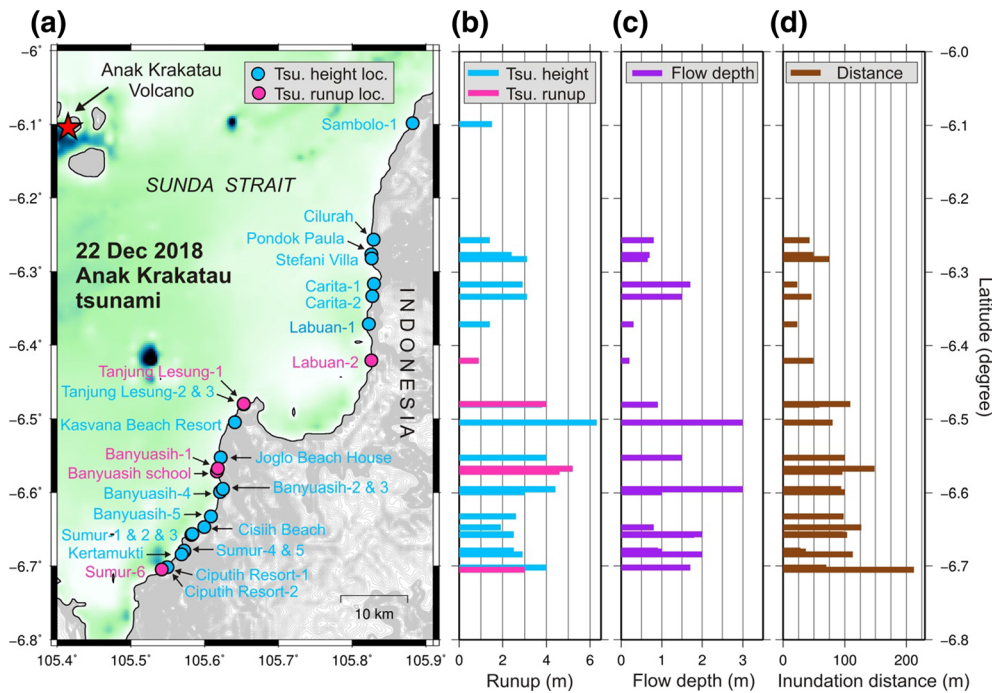


Figure 4

Results of field surveys of the 2018 Anak Krakatau volcano tsunami along the coast of Sunda Strait. **a** Locations of measurements including tsunami runup (pink) and tsunami height (cyan). **b** Results of tsunami runup (pink) and tsunami height (cyan) measurements. **c** Flow depth measurements. **d** Inundation distances. “Tsu.” and “Loc.” are abbreviations for “Tsunami” and “Locations”, respectively

and the death toll was nine based on interviews with local residents. In general, our survey results are consistent with previous field survey reports by Muhari et al. (2019) and Putra et al. (2020) in terms of reporting maximum tsunami runup to the south of Tanjung Lesung and also in term of average range of tsunami heights. We note that our maximum height is 6.3 m while it was 13 m in Muhari et al. (2019) and Putra et al. (2020). The reason is that the 13 m runup occurred along a narrow segment of the Sunda Strait coast at a cliff-type coast in an uninhabited location with no damage to properties; thus, we did not survey that location as the scope of this study was to visit locations that sustained large destruction and loss of life. In the following, we briefly describe the survey locations and the situation of tsunami runup and height measurements at each survey point.

4.1. Sambolo-1, Cilurah and Pondok Paula

No tsunami death was identified based on interviews with local eyewitnesses in Sambolo-1, Cilurah

and Pondok Paula. The tsunami heights in these three locations were in the range of 1.5–2.4 m with flow depths of less than 1 m (Fig. 5). Sambolo-1 is a low-lying coast with sandy beach, packed with tourists at the time of the survey (Fig. 5a). The flat coast here is elevated approximately 1.5 m from the high tide level. Beyond this step, the coast is flat until it reaches a coastal road at the distance of approximately 50 m which is slightly elevated (~ 0.5 m) compared to the flat beach elevation. The tsunami was stopped at the shoreline step and was not capable of flooding the flat plane in Sambolo-1. Cilurah is a small fishing harbor and a low-lying coast with a coastal berm elevated ~ 1 m (Fig. 5b). Tsunami watermark with a flow depth of 0.8 m (from the ground level) was clear at a small masonry building located at the distance of 50 m from the coast (Fig. 5c, d). Relatively larger tsunami height of 2.4 m was measured in Pondok Paula where a few building were damaged by the tsunami (Fig. 5e, f). Big part of a house, located approximately 20 m from the coast,

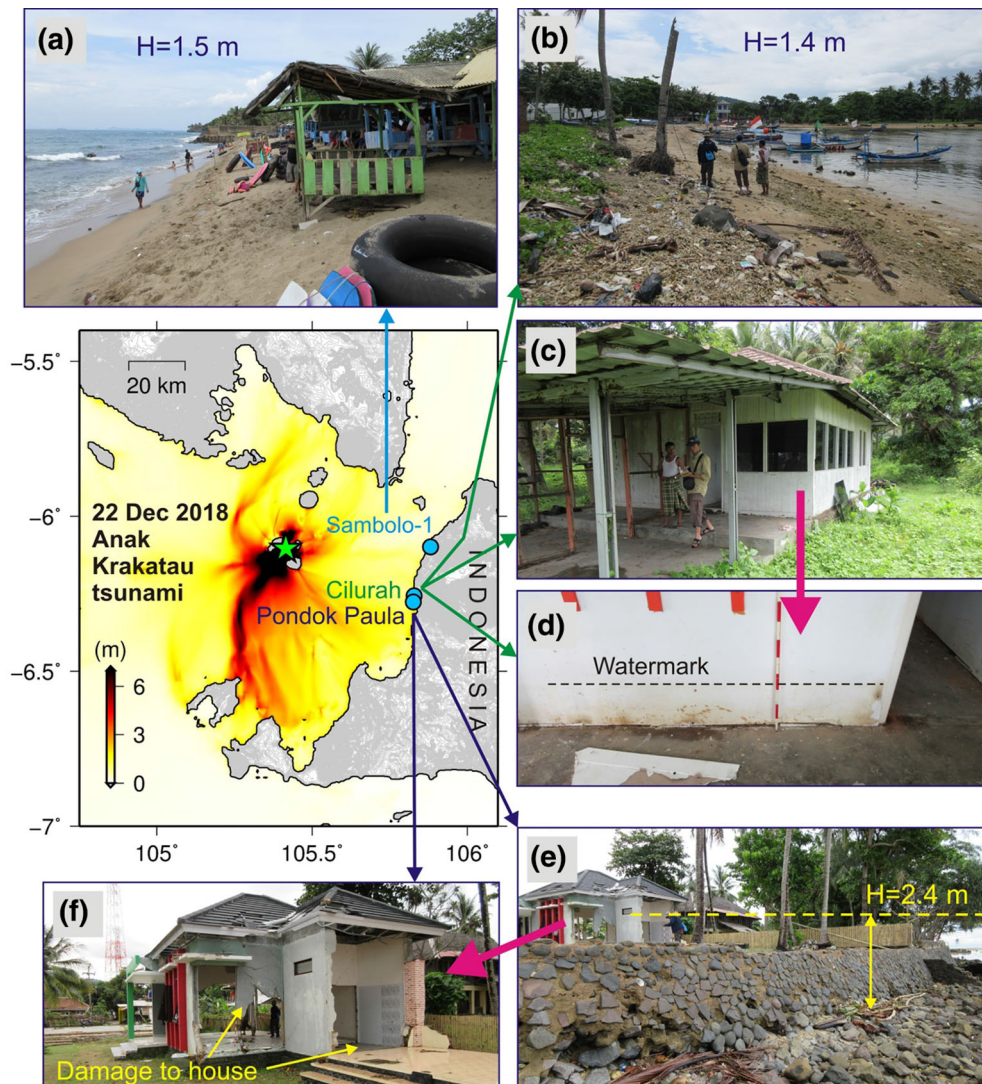


Figure 5

Field surveys of the 2018 Anak Krakatau volcano tsunami at three locations Sambolo-1 (a), Cilurah (b–d) and Pondok Paula (e, f). “H” stands for tsunami height. Dashed lines show tsunami elevations

was washed away by the tsunami in Pondok Paula (Fig. 5e, f).

4.2. Stefani Villa

Stefani Villa was full of guests spending their Christmas and new-year holidays at the time of the tsunami (Fig. 6). The caretaker of this villa told us that 46 people were killed here; thus making this site an important location for studying the AKT’s

destructive effects. A 50-m long riprap jetty is installed in front of the villa (Fig. 6d, e). We measured a wave height of 3.1 m with flow depth of 0.65 m (Fig. 6b). Severe tsunami impacts were observed for the few rooms closest to the shore (Fig. 6a). The villa rooms were located at the distance of 40–100 m from the shoreline. An open pool at the shore-side of the villa still contained large stones at the time of our survey that appear to be part of the riprap jetty (Fig. 6d, e); these large stones were

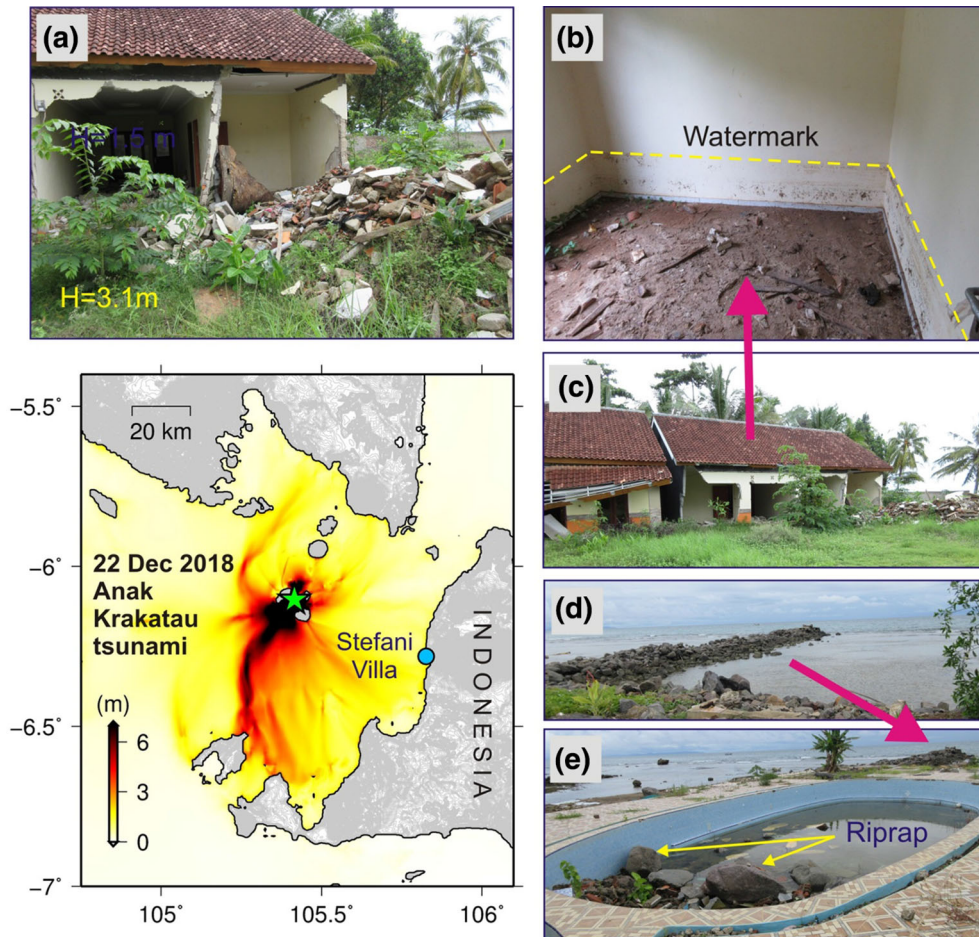


Figure 6

Field surveys of the 2018 Anak Krakatau volcano tsunami at Stefani Villa. “H” stands for tsunami height. Dashed lines show tsunami elevations

most likely transferred to the pool by the tsunami. The death toll here appears to be disproportionate to the moderate tsunami height and flow depth that we recorded here. In addition, this area of the Sunda Strait coastline is not on the direct tsunami energy beam as inferred from maximum tsunami height map (Fig. 3a). It is therefore puzzling how such a large number of fatalities occurred at this location. Several factors may have contributed to excessive death toll here such as: debris impact, in particular from the riprap jetty transferred by the tsunami (Fig. 6d, e); construction design shortcoming in the form of lack of any step between the villa rooms and the ground level (such steps could stop large debris from directly impacting people inside the rooms); lack of escape

routes as we were informed by the villa caretaker that the villa area was tightly locked down at the night of the tsunami attack.

4.3. Carita

Several houses were fully washed away in location Carita-1 where tsunami height and flow depth were 2.9 m and 1.7 m, respectively (Table 1; Fig. 7). We were informed by local eyewitnesses that 10 lives were lost here. However, a house in the nearby (Fig. 7a) survived with little damage, which helped us to identify watermark and to measure tsunami height. The houses that were washed away here were mainly located at places where the seawall

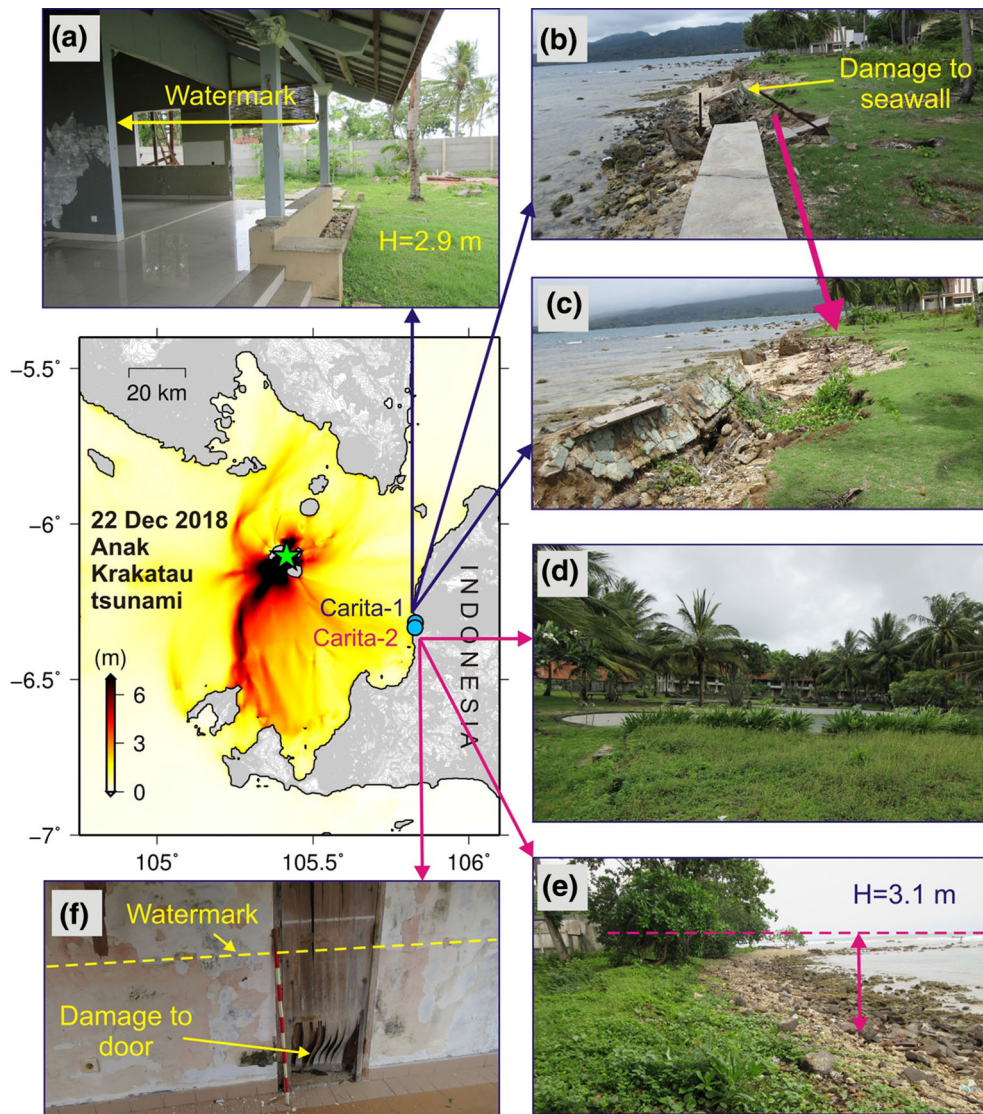


Figure 7

Field surveys of the 2018 Anak Krakatau volcano tsunami in Carita. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively

was destroyed (Fig. 7b, c) while the seawall at the location of the survived house was intact. Location Carita-2 is an abandoned hotel (i.e. abandoned from decades ago) with low-lying beach (Fig. 7d). The tsunami height and flow depth in Carita-2 were 3.1 m and 1.5 m, respectively (Table 1; Fig. 7). Tsunami watermark and damage were clear in many hotel rooms in Carita-2 (Fig. 7f).

4.4. Labuan

Two places in Labuan were surveyed, Labuan-1 and Labuan-2, where we measured tsunami height and runup of 1.4 m and 0.9 m, respectively (Fig. 8). This part of the Sunda Strait coastline, which is characterized by low-lying areas, received low tsunami height and runup. Labuan-1 has been a densely-populated coastal village with houses located as close as 10–20 m from the shoreline. Although the

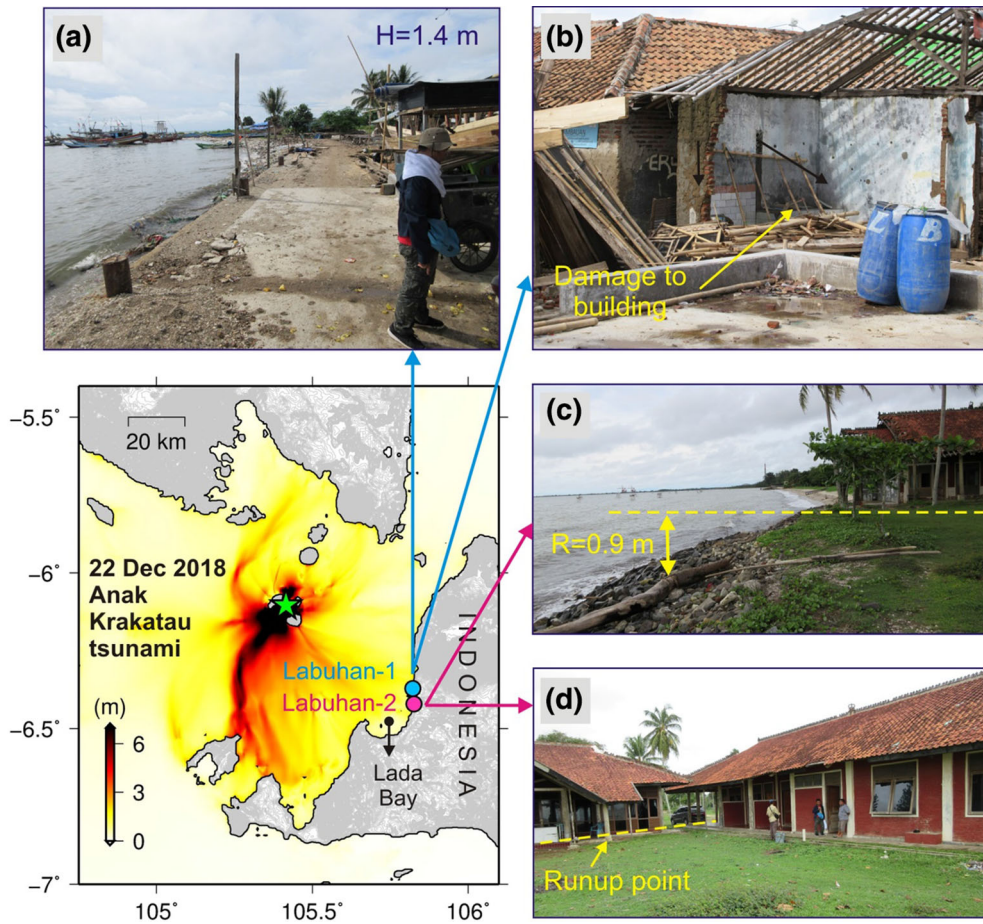


Figure 8

Field surveys of the 2018 Anak Krakatau volcano tsunami in Labuan. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively

tsunami height was small in Labuan-1 (i.e. 1.4 m), a few houses were washed away (Fig. 8b) and there were two deaths here which can be attributed to the short distance of the residential areas to the shore (i.e. 10–20 m). Similar to Labuan-1, a low-lying coastal area was seen in Labuan-2 (Fig. 8c, d). By interviewing with eyewitnesses, we measured a runup of 0.9 m and inundation distance of 49 m. The lowest runup during our survey was recorded in Labuan-2 (i.e. 0.9 m). As this area is located inside the Lada Bay (Fig. 8), in general, the coastal areas are protected against tsunamis.

4.5. Tanjung Lesung

One of the tragedies during the AKT occurred in Tanjung Lesung coastal resort where more than 50 people were killed while attending an outdoor music concert a few meters away from the shore (Fig. 9c). The area is flat and low-lying (Fig. 9). This incident possibly implies that the level of tsunami hazard understanding by local people was not adequate as they chose to hold a music concert at the shore while the AKV has been showing obvious signs of activity for a few months before the tsunami (Emile A. Okal, personal communications). We measured tsunami height and runup of 2.9–4.0 m in this location. Damage was observed in some of the resort’s villas (Fig. 9d, e). Watermark and debris’ impacts also

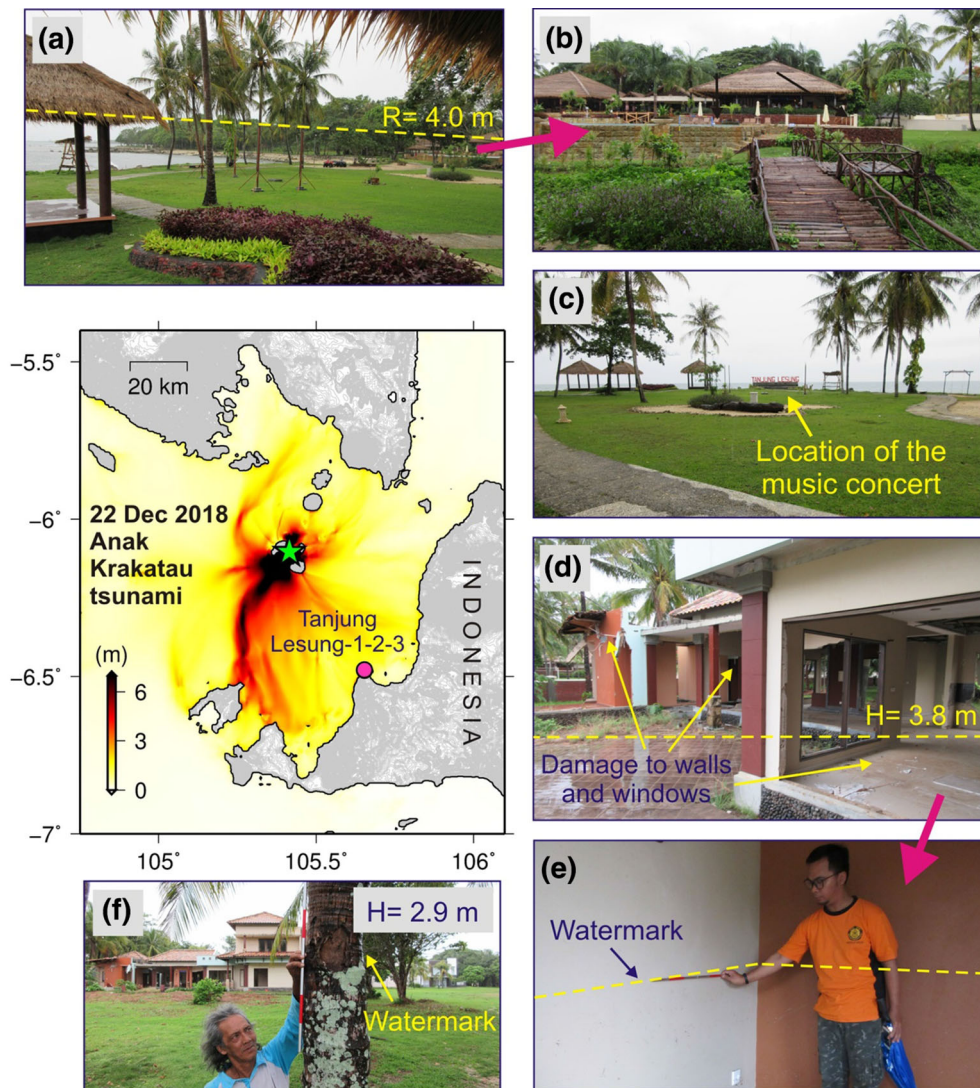


Figure 9

Field surveys of the 2018 Anak Krakatau volcano tsunami in Tanjung Lesung. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively

were found on other buildings and trees in the area (Fig. 9f). The Tanjung Lesung tragedy could be prevented if the general awareness of tsunami and public education could be better and the music concert was not held at the shoreline while the AKV was showing obvious signs of activity for a few months. At the same time, the government needs to invest more on national tsunami warning systems as no warning was made to public before the arrival of the 2018 tsunami.

4.6. Kasavana Beach Resort and Joglo Beach house

The two beach houses of Kasavana and Joglo suffered a combined death toll of 18; with each of them reporting nine deaths (Fig. 10). In Kasavana Beach Resort, several villas located close to the sea were either completely or partially washed away (Fig. 10a) as a result of a tsunami height of 6.3 m here. This is the largest tsunami height recorded during this field survey. We recorded flow depths of

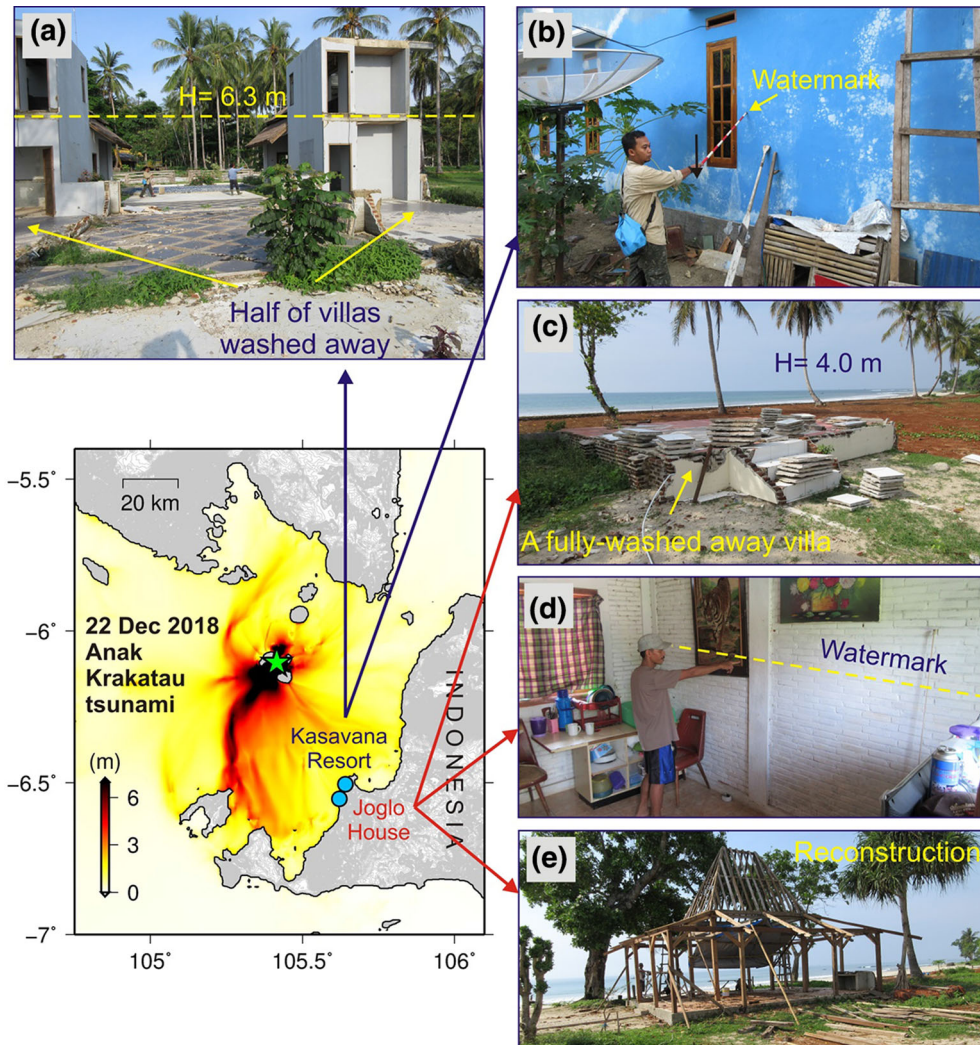


Figure 10

Field surveys of the 2018 Anak Krakatau volcano tsunami in Kasavana Beach Resort and Joglo Beach house. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively

up to 3.0 m in Kasavana Beach Resort (Fig. 10a, b). During conversations with the owners of this resort, we realized that they are planning to move the villas farther away from the coast (i.e. 150–200 m) in order to provide tsunami resilience to future events. Similar situation was observed in Joglo Beach House (Fig. 10c–e) where tsunami height and flow depth were 4.0 m and 1.5 m, respectively. Figure 10c shows a completely-washed away villa which was located approximately 30 m from the shoreline. However, a villa located at the distance of 100 m from the shoreline suffered little damage (Fig. 10d).

Reconstruction was ongoing in the Joglo Beach House at the time of the survey where villas were re-installed at around the same place of the damaged villas; at close vicinity of the shoreline (Fig. 10e). This may not be a wise reconstruction practice since the new villas would be exposed to the same level of tsunami risk as the damaged ones. The post-tsunami situation here may itself tell that a distance of approximately 100 m from the shoreline (Fig. 10d) could save lives and properties during this event. We note that the point about “100 m distance from the

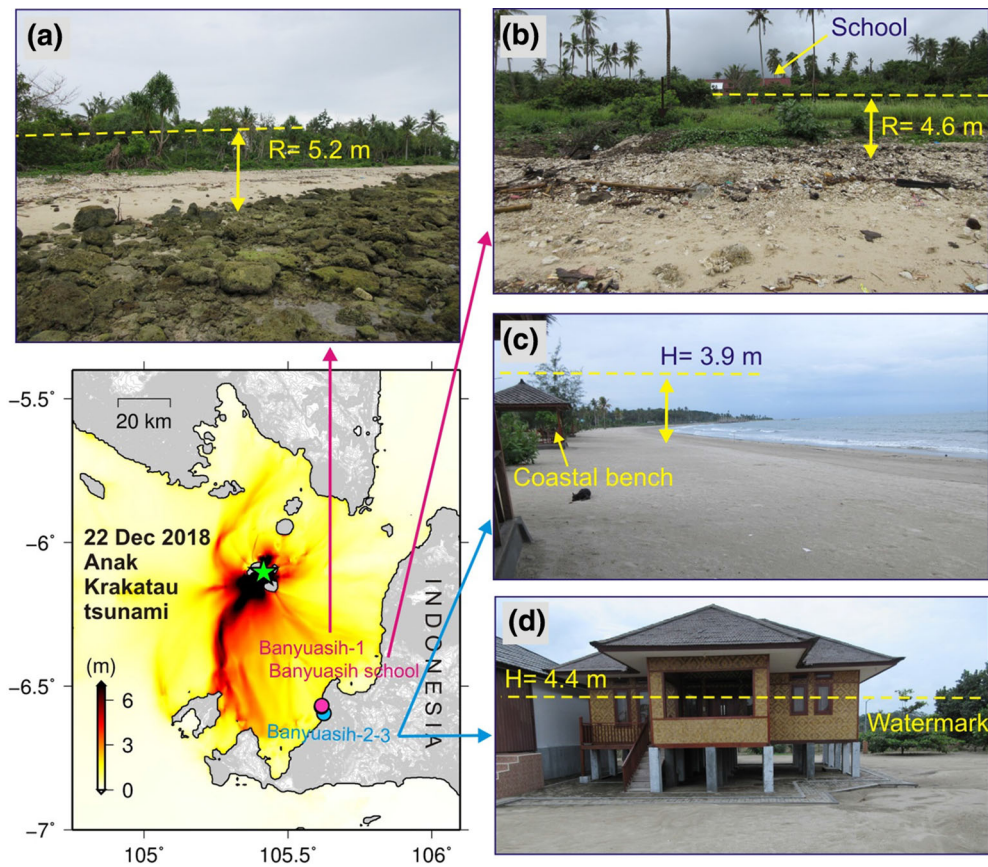


Figure 11

Field surveys of the 2018 Anak Krakatau volcano tsunami in Banyuasih-1, Banyuasih School and Banyuasih-2-3. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively. Note that the photo in “d” show a reconstructed villa after the tsunami

coast” is applicable only for the 2018 event and it could be different in the case of another tsunami.

4.7. Banyuasih-1, Banyuasih School and Banyuasih-2-3

The location Banyuasih-1 was around a coastal village where houses were distanced a few hundreds of meters from the coast (Fig. 11a). We measured a tsunami runup and inundation distance of 5.2 m and 148 m, respectively. At the Banyuasih School (Fig. 11b), tsunami runup and inundation distance were 4.6 m and 96 m, respectively. The flow depth inside the school was 10–20 cm. This school is located on top of a small hill which is elevated ~ 3 m from the surrounding areas. Through

interviews with locals, no tsunami death was reported in this area which is possibly due to the relatively long distances between the shoreline and residential areas (Fig. 11a, b). A coastal resort was located at Banyuasih-2 and -3 where we measured wave heights of 3.9–4.4 m (Fig. 11c, d). Two deaths were reported at this resort by the resort’s caretaker; the two victims were sitting at a coastal bench of this resort at the tsunami time (Fig. 11c).

4.8. Banyuasih-4 and -5 and the Cisiuh Beach

With tsunami height and flow depth of 3.0 m and 1.0 m, respectively, buildings in Banyuasih-4 sustained some damage but no death was incurred (Fig. 12a, b). At Banyuasih-5, damage was observed

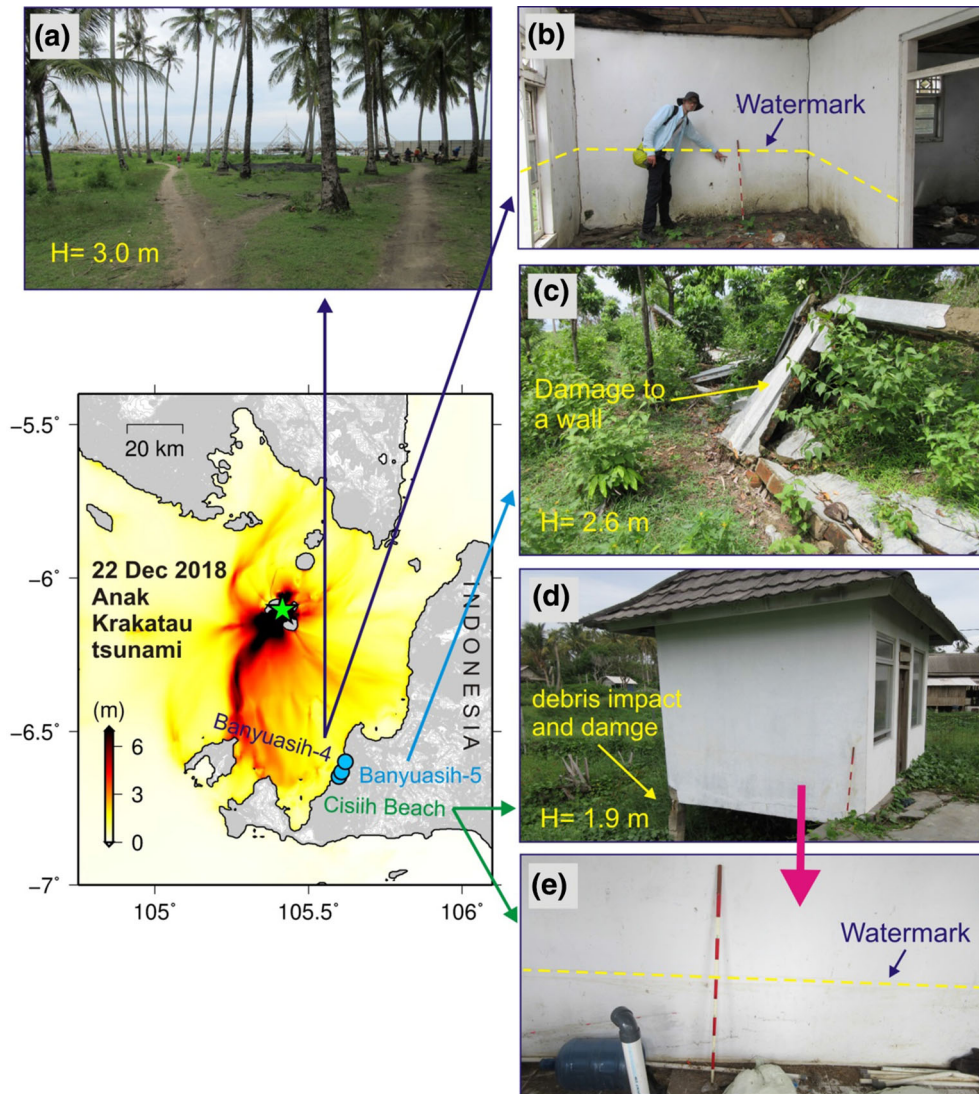


Figure 12

Field surveys of the 2018 Anak Krakatau volcano tsunami in Banyuasih-4 and -5 and the Cisih Beach. Dashed lines show tsunami flow elevations. “H” stands for tsunami height

to some walls of a property where an engineered structure with steel reinforcement was overturned (Fig. 12c). Similar situation was observed in a coastal park in Cisih Beach where a small room for the security personnel at the entrance of the park sustained some damage from debris impacts (Fig. 12d). Clear watermark was found inside this security room (Fig. 12e) which helped us to measure a tsunami height of 1.9 m for this location.

4.9. Sumur-1, -2 and -3

Sumur is characterized by relatively lower tsunami heights (i.e. $H = 2.0\text{--}3.0$ m) but with significant damage and loss of life. In total, Sumur suffered around 70 deaths based on our interviews with local eyewitnesses. Location Sumur-1 is a populated coastal village hosting a traditional fish market (Fig. 13a) which experienced a wave height of 2.4 m resulting in complete destruction of multiple houses; here, 11 houses were washed away based on

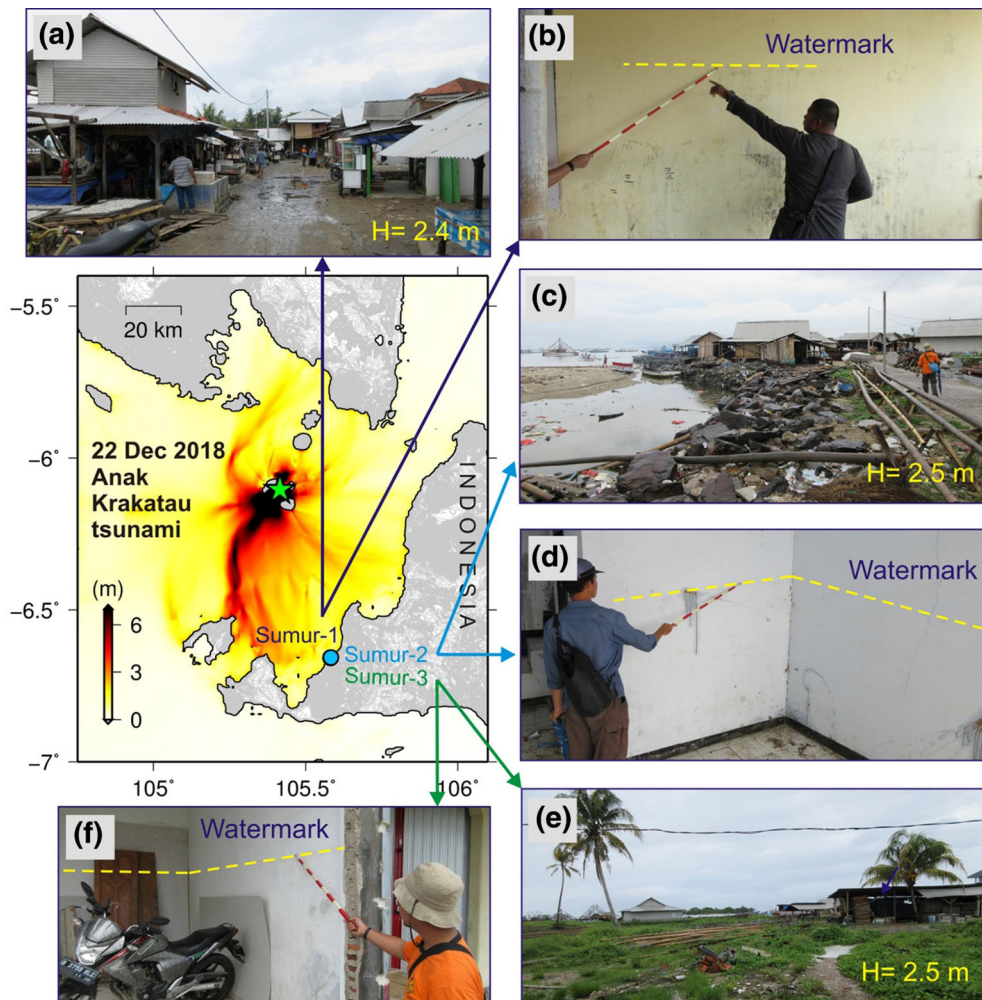


Figure 13

Field surveys of the 2018 Anak Krakatau volcano tsunami in Sumur-1, -2 and -3. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively

interviews with two eyewitnesses who reported two different numbers of seven and 10 for the death toll at this location. Similar to Sumur-1, several houses were completely washed away in Sumur-2 despite a relatively low tsunami height of 2.5 m (Fig. 13c, d). Multiple people were killed in Sumur-2. Tsunami height was 2.5 m in location Sumur-3 where four people lost their lives (Fig. 13e, f). We found clear watermarks in all three locations Sumur-1, -2 and -3 (Fig. 13b, d, f). An eyewitness in Sumur-3 reported he and his family evacuated right after the first wave hit the coast because he felt something unusual was going on although he had no idea a tsunami was

coming. The number of death and level of destruction in Sumur appears to be unusually high which can be attributed to the extremely low-lying coastal land in this part of the Sunda Strait coast.

4.10. Sumur-4, -5 and Kertamukti

Consistent with other locations in Sumur, the three locations Sumur-4, -5 and Kertamukti received tsunami heights of 2.3–2.9 m (Fig. 14). A large boulder with dimension of approximately 1.5 m × 1.5 m × 1.5 m was transferred around 30 m inland in Sumur-4 (Fig. 14a). It was confirmed

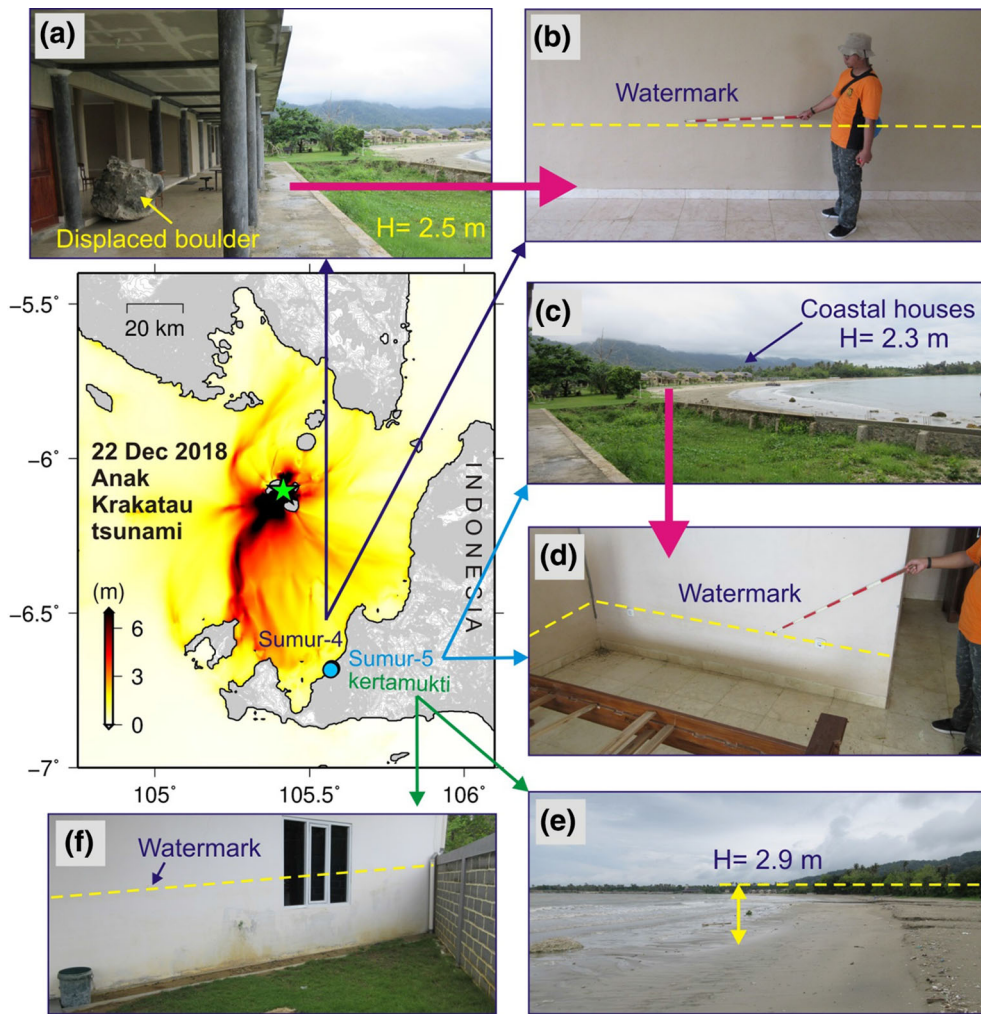


Figure 14

Field surveys of the 2018 Anak Krakatau volcano tsunami in Sumur-4, -5 and Kertamukti. Dashed lines show tsunami flow elevations. “H” and “R” stand for tsunami height and runup, respectively

by an eyewitness that the boulder was transferred by the AKT. The location Sumur-5 was the site of an incomplete residential complex. Location Kertamukti was a guest house where the tsunami height was measured at 2.9 m. The caretaker of the guest house reported no death occurred there during this tsunami which is most likely because the guest house is located approximately 100 m from the coast. Watermarks were clear in all locations (Fig. 14b, d, f).

4.11. Ciputih Resort -1, -2 and Sumur-6

Two locations were surveyed in Ciputih Resort (i.e. Ciputih Resort-1 and -2) and tsunami heights and flow depths were measured at 3.9–4.0 m and 1.2–1.7 m, respectively (Fig. 15a–c). Hotel villas located at the close vicinity of the shore (< 20 m) were either completely (Fig. 15c) or partially (Fig. 15b) washed away by the tsunami resulting in a death toll of 15 here (based on eyewitness accounts). Other villas located at the back with distances of > 70 m from the coast sustained small damage to furniture but their structure remained

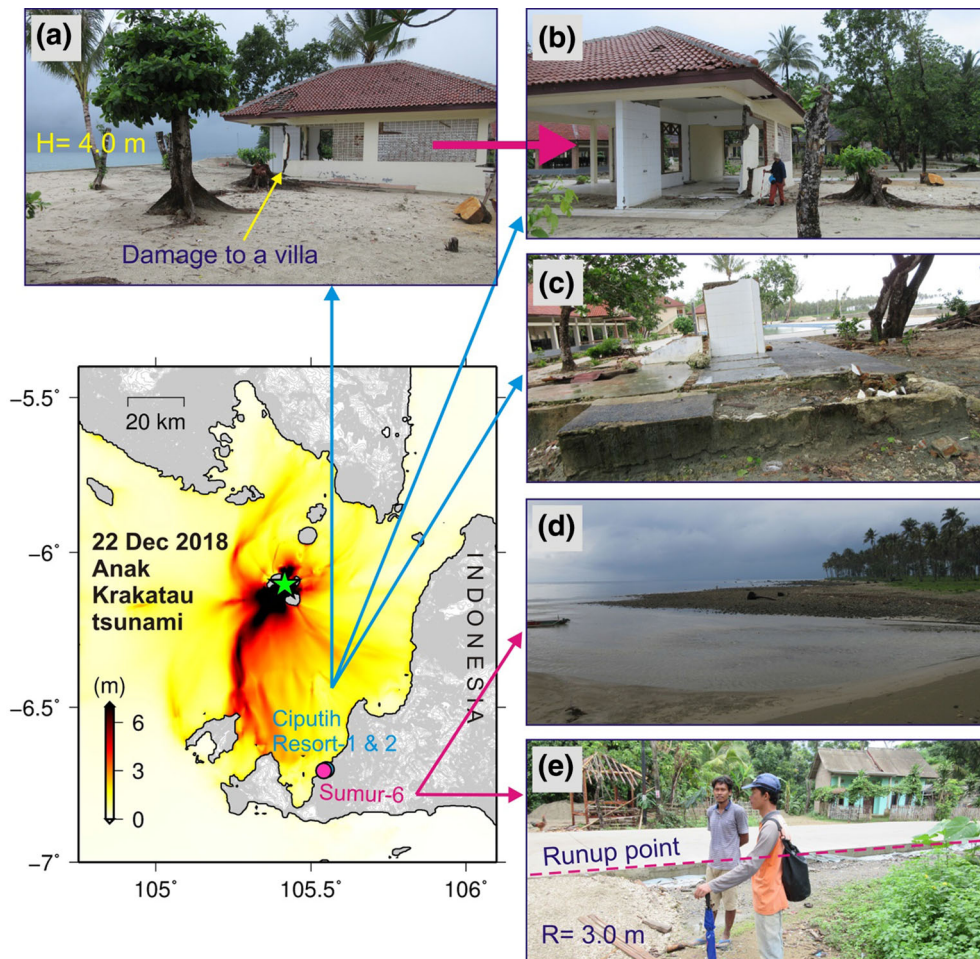


Figure 15

Field surveys of the 2018 Anak Krakatau volcano tsunami in Ciputih Resort -1, -2 and Sumur-6. Dashed lines show tsunami flow elevations. "H" and "R" stand for tsunami height and runup, respectively

intact. This is another piece of evidence showing a distance of approximately 100 m for the villas from the shoreline could save the lives lost here during this tsunami. In location Sumur-6, we found a small coastal community located approximately 150–200 m from the shoreline (Fig. 15d, e). Eyewitnesses reported that the AKT reached the village's main road but did not overtop it; this implies a runup of 3.0 m and an inundation distance of 212 m. No death was reported by the eyewitnesses here which is easily conceivable due to the long distance (i.e. 150–200 m) from the shoreline to the village.

5. Conclusions

The areas damaged by the tsunami resulting from the eruption of the Anak Krakatau Volcano (AKV) on 22 December 2018 were surveyed to record tsunami heights and runups and to assess tsunami damage. The findings are:

- The field surveys of this study found tsunami runup (R), tsunami heights (H), flow depths (D) and inundation distances (L) of $R = 0.9\text{--}5.2$ m, $H = 1.4\text{--}6.3$ m, $D = 0.2\text{--}3.0$ m and $L = 18\text{--}212$ m, respectively. The largest tsunami height and destruction/death were concentrated to

the part of the Sunda Strait coast from Tanjung Lesung to Sumur.

- At Stefani Villa, 46 people were killed by a tsunami with amplitude of 3.1 m. We believe that several factors led to this tragedy including: debris impacts from the stones of the riprap jetty; design shortcomings as there was no step between the villa rooms and the ground level; and lack of escape routes in the villa.
- In some low-lying locations, like Labuan, with houses located very close to the coast (i.e. 10–20 m), a small tsunami with height of 1.4 m cost two lives. This may indicate that distance of the houses from the coast is a decisive factor in tsunami death.
- The main reason for the Tanjung Lesung tragedy, where more than 50 people were killed while attending an outdoor music concert, was that the event was held at the shoreline. We believe that the Tanjung Lesung tragedy could be prevented if the general awareness of tsunami could be better and the music concert was not held at the shoreline while the AKV was showing obvious signs of activity for a few months; at least 100 m distance from the shoreline could save those lives during this event.
- While some of the owners of the damaged beach resorts were planning to move the villas to a few hundred meters away from the shoreline, others were reconstructing the damaged villas at the same place. Obviously, it may not be a wise reconstruction practice since the new villas would be at the same risk as the damaged ones.
- Based on surveys of several tsunami damage/death locations along the coast of the Sunda Strait, it appears that most casualties and destruction were concentrated within 100 m from the coastline during this event. In several locations, such as Banyuasih School, lives were saved where buildings were located approximately 100 m and longer from the shoreline.
- Significant damage and death was observed in Sumur, although tsunami heights there were measured as moderate (i.e. $H = 2.0\text{--}3.0$ m). The damage/death in Sumur appears unusually high which can be attributed to the extremely low-lying coastal land here.

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REFERENCES

- Borrero, J. C., Solihuddin, T., Fritz, H. M., Lynett, P. J., et al. (2020). Field survey and numerical modelling of the December 22, 2018 Anak Krakatau Tsunami. *Pure and Applied Geophysics*. <https://doi.org/10.1007/s00024-020-02515-y>.

- Fritz, H. M., Synolakis, C. E., & McAdoo, B. G. (2006). Maldives field survey after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, 22(S3), 137–154.
- Grilli, S. T., Tappin, D. R., Carey, S., et al. (2019). Modelling of the tsunami from the December 22, 2018 lateral collapse of Anak Krakatau volcano in the Sunda Straits, Indonesia. *Scientific Reports*, 9(1), 1–13.
- Heidarzadeh, M., Harada, T., Satake, K., Ishibe, T., & Gusman, A. (2016). Comparative study of two tsunamigenic earthquakes in the Solomon Islands: 2015 Mw 7.0 normal-fault and 2013 Santa Cruz Mw 8.0 megathrust earthquakes. *Geophysical Research Letters*, 43(9), 4340–4349.
- Heidarzadeh, M., Ishibe, T., Sandanbata, O., Muhari, A., & Wijanarto, A. B. (2020a). Numerical modeling of the subaerial landslide source of the 22 December 2018 Anak Krakatau volcanic tsunami, Indonesia. *Ocean Engineering*. <https://doi.org/10.1016/j.oceaneng.2019.106733>.
- Heidarzadeh, M., Necmioglu, O., Ishibe, T., & Yalciner, A. C. (2017). Bodrum-Kos (Turkey-Greece) Mw 6.6 earthquake and tsunami of 20 July 2017: A test for the Mediterranean tsunami warning system. *Geoscience Letters*, 4, 31. <https://doi.org/10.1186/s40562-017-0097-0>.
- Heidarzadeh, M., Rabinovich, A. B., Kusumoto, S., & Rajendran, C. P. (2020b). Field surveys and numerical modeling of the 26 December 2004 Indian Ocean tsunami in the area of Mumbai, west coast of India. *Geophysical Journal International*, 222, 1952–1964. <https://doi.org/10.1093/gji/ggaa277>.
- Heidarzadeh, M., Teeuw, R., Day, S., & Solana, C. (2018). Storm wave runups and sea level variations for the September 2017 Hurricane Maria along the coast of Dominica, eastern Caribbean Sea: Evidence from field surveys and sea level data analysis. *Coastal Engineering Journal*, 60(3), 371–384. <https://doi.org/10.1080/21664250.2018.1546269>.
- Muhari, A., Heidarzadeh, M., Susmoro, H., et al. (2019). The December 2018 Anak Krakatau volcano tsunami as inferred from post-tsunami field surveys and spectral analysis. *Pure and Applied Geophysics*, 176, 5219–5233. <https://doi.org/10.1007/s00024-019-02358-2>.
- Paris, A., Heinrich, P., Paris, R., & Abadie, S. (2020). The December 22, 2018 Anak Krakatau, Indonesia, landslide and tsunami: Preliminary modeling results. *Pure and Applied Geophysics*, 177(2), 571–590. <https://doi.org/10.1007/s00024-019-02394-y>.
- Putra, P. S., Aswan, A., Maryunani, K. A., Yulianto, E., Nugroho, S. H., & Setiawan, V. (2020). Post-event field survey of the 22 December 2018 Anak Krakatau tsunami. *Pure and Applied Geophysics*, 177, 1–16. <https://doi.org/10.1007/s00024-020-02446-8>.
- Ren, Z., Wang, Y., Wang, P., Hou, J., Gao, Y., & Zhao, L. (2020). Numerical study of the triggering mechanism of the 2018 Anak Krakatau tsunami: Eruption or collapsed landslide? *Natural Hazards*. <https://doi.org/10.1007/s11069-020-03907-y>.
- Satake, K., Heidarzadeh, M., Quiroz, M., & Cienfuegos, R. (2020). History and features of trans-oceanic tsunamis and implications for paleo-tsunami studies. *Earth-Science Reviews*, 202, 103112. <https://doi.org/10.1016/j.earscirev.2020.103112>.
- Satake, K., & Heidarzadeh, M. (2017). A review of source models of the 2015 Illapel, Chile earthquake and insights from tsunami data. *Pure and Applied Geophysics*, 174(1), 1–9. <https://doi.org/10.1007/s00024-016-1450-5>.
- Synolakis, C. E., & Okal, E. A. (2005). 1992–2002: Perspective on a decade of post-tsunami surveys. In K. Satake (Ed.), *Tsunami, advances in natural and technological hazards* (Vol. 23, pp. 1–29). Dordrecht: Springer.
- Tsuji, Y., Satake, K., Ishibe, T., et al. (2011). Field surveys of tsunami heights from the 2011 off the Pacific coast of Tohoku, Japan earthquake. *Bulletin of the Earthquake Research Institute of the University of Tokyo*, 86, 29–279.
- Wessel, P., & Smith, W. H. F. (1998). New, improved version of generic mapping tools released. *EOS Transactions of AGU*, 79(47), 579. <https://doi.org/10.1029/98EO00426>.
- Zengaffinen, T., Løvholt, F., Pedersen, G. K., & Muhari, A. (2020). Modelling 2018 Anak Krakatau flank collapse and tsunami-effect of landslide failure mechanism and dynamics on tsunami generation. *Pure and Applied Geophysics*, 177, 2493–2516. <https://doi.org/10.1007/s00024-020-02489-x>.

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