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Field Survey of Flank Collapse and Run-up Heights due to 2018 Anak Krakatau Tsunami

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Abstract

On the 22nd of December 2018 tsunami waves generated by the flank collapse of the Anak Krakatau volcano in Indonesia flooded the shorelines of the nearby Sumatra and Java islands. The authors conducted a field survey of the Krakatau archipelago to clarify the volume of the collapsed flank and the run-up of the tsunami around the islands themselves. To aid with the simulation of this complex tsunami and document the current situation of the islands, bathymetric surveys, aerial drone and panoramic video mapping were also carried out. Using DEM of Anak Krakatau before and after the eruptions and tsunami, the authors could calculate the volume of flank collapse, which was estimated to be 0.286-0.574 km^3. The run-ups that were measured were particularly significant, over 80 m in height in Panjang Island. While much of the source directionally was towards the SE of Anak Krakatau, significant wave run-ups were also measured towards the NW, indicating that further numerical modelling is needed to fully explain this event. The estimation of such parameters is of vital importance for the design of structures to protect and enhance the resilience of human settlements in at-risk areas.

Keywords

Tsunami, Landslide, Krakatau, Field survey

1 Introduction

Landslides can generate significant tsunamis, with a number of significant events having taken place in recent decades. In 1963, a subaerial landslide at Vajont Dam, Italy, impacted a reservoir and generated a significant wave, causing more than 2,000 fatalities (Panizzo et al., 2005; Genevois and Ghirotti, 2005). During the 1988 Papua New Guinea earthquake, it is believed that a submarine landslide generated a tsunami having over 15 m at Sissano split (Tappin et al. 2001, 2008). In 2007, subaerial landslides at Chehalis Lake in British Columbia, Canada, caused tsunami run-ups of 38 m (Brideau et al., 2012). In the 2010 Haiti Earthquake, coastal landslides caused by an earthquake generated local tsunami waves of up to 3 m (Fritz et al. 2013). During the 2018 Palu Earthquake, multiple submarine landslides generated devastating tsunamis with inundations height of up to 5 m in the City of Palu and the Donggala Regency, in Sulawesi Island, Indonesia, (Sassa and Takagawa 2019; Mikami et al. 2019; Stolle et al. 2020; Harnantyari et al. 2020).

At 21:30 local time (UTC+7h) on the 22nd of December 2018 the shorelines of the Sunda Strait, Indonesia, were flooded by tsunami waves. The inundation caused widespread destruction and resulted in 437 casualties, 31`943 injuries, 10 still missing and over 16,000 people displaced (as of the 14th January 2019 National Disaster Management Agency (BNBP), 2019). The tsunami was caused by the flank collapse of the Anak Krakatau volcano (Robertson et al. 2018; TDMRC 2018, Takabatake et al., 2019, Grilli et al., 2019), located roughly at the centre of the Sunda Strait, which separates the Southern Sumatra and western Java islands. Satellite images by the Geospatial Information Authority of Japan (2018) show a comparison of Anak Krakatau before (2018/08/20) and after (2018/12/24) the event, clearly identifying the collapse of the southwest side of the volcano. The volume of material that was displaced from it between the 24th and 27th of December was estimated to be 0.15-0.17 km^3, though these rough calculations require a more detailed verification (Geospatial Information Authority of Japan, 2018).

The explosion of Krakatau island in August 1883 is a famous event in volcanology and the history of tsunamis. As a result of it, most of the island was destroyed (Van den Bergh et al. 2003), and a major tsunami was generated, causing widespread damage to the coastlines around the Sunda Strait. Pararas-Carayannis (2003) report that around 300 coastal towns and villages were destroyed by waves up to 37 m in height, resulting in over 36,000 casualties. The Krakatau volcano has continued to be active since then, and in 1927 Anak Krakatau (literally “the child of Krakatau” in Bahasa Indonesia) emerged above the sea from the remnants of the original volcano (Hoffmann-Rothe et al. 2006).

The steep side of Anak Krakatau had been deemed unstable for some time (see Giachetti et al., 2012), and there was a known risk that it could collapse and cause a tsunami. Despite this, the 2018 tsunami event caught local residents and the authorities by surprise, even when the volcano had been active since June 2018. Essentially, the Indonesian tsunami warning system is based on ocean buoys that aim to detect the tsunamis that are generated by submarine earthquakes Rudloff et al. (2009) and Lauterjung et al. (2010), and not those by submarine landslides or volcanic eruptions (which might have different characteristics, such as shorter wave periods, see Takagi et al., 2019, Mikami et al., 2019). Also, it would appear that many of the instruments that had been installed after the *2004 Indian Ocean Tsunami* were not operating in 2018, and in any case they were mostly placed along the subduction zone of the Indonesian islands, and not close to Anak Krakatau (Robertson et al. 2018).

A number of researchers have investigated the types of tsunamis that can be triggered by volcanic events (e.g., Waythomas and Watts 2003; Choi et al. 2003; Maeno et al. 2006; Maeno and Imamura 2011), even though they are less frequent than those generated by submarine earthquakes (Paris et al. 2014). Takabatake et al. (2019) performed a field survey of the affected areas to clarify the hazard mechanism, evacuation patterns and run-up and inundation heights due to the *2018 Sunda Strait tsunami*. The survey results showed that inundation heights were more than 4 m high along the coastline of Sumatra island (situated to the north-north-east of Anak Krakatau), while less than 4 m were measured along the north-western direction. In Java island inundation heights of over 10 m were measured at Cipenyu Beach (south-south-eastern direction from Anak Krakatau). Similar tsunami distributions in Sumatra and Java islands were also reported by Muhari et al. (2019) and Syamsidik et al. (2020). Takabatake et al. (2019) also conducted a questionnaire survey of those affected by the event, showing relatively high levels of tsunami awareness. However, the lack of warning and congestion along evacuation routes were identified as important problems in disaster risk management, and can explain the large number of casualties despite the relatively modest inundation heights.

Grilli et al. (2019) performed simulations to attempt to clarify the tsunami generation and propagation mechanisms. However, such research was based on a number of assumptions, notably the absence of a reliable bathymetry or measurements of the size and extent of the volume of the landslide. The challenges of producing reliable simulations without having a reliable bathymetry are mentioned by Heidarzadeh et al. (2020), who approximated the tsunami wave by trial and error using twelve source models. This is a recurring problem for other authors, who have had to rely on witness photography to estimate the possible run-ups (Paris et al., 2019), or on the parameters proposed by Grilli et al, 2019 (for example Ren et al., 2020)

A number of authors have attempted to find out more details about the volume of the flank collapse, for example through the use of synthetic aperture radar (SAT) satellites (Williams et al. 2019). However, to the authors’ knowledge, the only actual field surveys conducted up to date around Anak Krakatau itself are by Borrero et al. (2020) in February 2019. While these authors report run-up heights, they did not conduct bathymetry measurements, and for their computer simulations they used a landslide scenario from before the actual 2018 eruption (thus failing to take into account for the actual changes that took place in the mountain).

In order to accurately simulate the 2018 tsunami it is thus necessary to estimate the collapsed volume, obtain a reliable bathymetry, and measure the run-ups generated due to the flank collapse of Anak Krakatau. To ascertain such parameters the authors conducted a field survey of the Krakatau islands, with the present paper summarising the main results and observations about the characteristics of the tsunami wave around this archipelago, together with their current bathymetry and geography. The appropriate estimation of such parameters is of vital importance for coastal engineers and disaster risk managers to design appropriate coastal structures that can withstand tsunamis, helping to protect the lives and possessions of individuals in at-risk areas.

2 Methodology

A field survey was conducted eight months after the volcanic eruption that generated the tsunami, between the 14th and 18th August 2019, focusing on the four islands that form the Krakatau group (the three remnants of the original Krakatau island and a fourth island, Anak Krakatau, that started to form in the early 20th century). The main objectives were to measure the run-up heights, establish how the tsunami propagated immediately after the flank collapse, estimate the volume of the material lost, and document the present state of the volcano to establish a benchmark to measure future geomorphological changes. For this purpose, a variety of complementary methods were employed, as summarised below.

2.1 Survey of run-up heights

The tsunami run-up heights on the side of the mountains were measured using a laser ranging instrument (IMPULSE 200LR (minimum reading: 0.01 m), Laser Technology Inc.), a prism and staffs. All heights were established using the sea water level as a reference point, and were corrected to the heights above the estimated tidal level at the time of the tsunami's arrival (estimated as 21:00 local time on the 22nd of December 2018) using a global tidal prediction software (WXtide32). The reference location for WXtide32 was Labuhan (the closest station among those included in the software, located at S6°22', E105°49', around 50 km away from Anak Krakatau), which has a tidal range of around 1 m. All data used in this paper corresponds to this corrected dataset. The precise location of each survey point was then recorded using GPS instruments (GPSMAP 64sc J, Garmin Ltd.), following established surveying techniques for these types of surveys (see Esteban et al. 2018).

Given the considerable time that had passed since the tsunami and the survey, these run-up heights represent lower-bound values (and it is likely that the actual values would have been higher). The height of the run-up was ascertained using direct observations of remaining damage to the vegetation, videos taken by government officials (as will be described later) and key informant interviews.

2.2 Bathymetry survey

The bathymetric surveys were conducted using two Garmin GPSMAP 585 echosounders (with two different transducers, GT20-TM for shallow water, and GT21-TM for deeper water), which were mounted on the two boats used during the survey (care was taken to keep the speed of the boat below 8 knots/hr, given the operational limitations of the instrumentation). The bathymetry data was analysed using QGIS 3.2 software, with the interpolation to produce contour maps being made using the Inverse Distance Weighting (IDW) method. The coastline was extracted from aerial images after the tsunami events obtained from Google Earth.

2.3 Aerial drone survey

An aerial drone survey of Anak Krakatau island (and part of the outer islands) was conducted using a Phantom 4 Pro+ unmanned aerial vehicle (UAV) (Da-Jiang Innovations Science and Technology Co. Ltd.). The aerial pictures were taken at vertical and diagonal angles to the ground level, covering almost 90% area of the volcanic island by flying at 150 m altitude. The overlap rate of the vertical pictures in the UAV forward moving direction ranged from 70% to 90%, to compensate the poor side lap rate between flight lines. Diagonal angle views were additionally included in structure from motion (SfM) process in order to increase the accuracy of constructed digital elevation map (DEM). The photogrammetric processes, including arrangement of the pictures and construction of the DEM, were conducted using Metashape 1.5.0 Professional Edition (AgiSoft). In these processes, the ground height close to the coastline was corrected to 0 m after the sea surface area was eliminated from each picture. Then, the absolute value of 90 and 75 percentiles on sorted negative elevation heights were added to the overall ground heights (75- and 90-case, hereafter).

The DEM of the island prior to the volcanic eruptions that caused the flank collapse were obtained from the three datasets mentioned hereafter. The ALOS World 3D (AW3D: Takaku and Tadono, 2017) data bought from NTT has a 2.5 m resolution terrain height generated from the stereo images by ALOS (Advanced Land Observing Satellite) in the period of 2006-2011. Seamless DEM dan Batimetri Nasional (DEMNAS: Badan Informasi Geospasial 2018a) provides 0.27 arc-second grid-space digital topographic and bathymetric heights around Indonesia. It is based on several different DEMs which are assimilated with real ground elevation. SRTM (Shuttle Radar Topography Mission: Farr et al. 2007) 1 arc second model is the result of interferometric radar measurement carried out in February 2000. These three DEM were subtracted from those generated by the data obtained through the UAV to obtain the volume of material that collapsed and generated the tsunami.

2.4 Underwater and above water 360˚ perimeter video survey

To document the changes to the perimeter of the island and the underwater characteristics of Anak Krakatau, 360˚ degree panoramic videos were taken using two Nikon KeyMission 360˚ cameras (panoramic 360, framerate 2160/24p). One of them was installed on top of one of the survey boats, and the other one under water, at a depth of 0.5 m. The boat sailed around the perimeter of the island, while simultaneously conducting the bathymetry survey of its perimeter.

2.5 Key informant interviews and collection of additional data

As part of the field survey the authors performed a number of informal non-structured key informant interviews with local government officers (tasked with guarding the area, as the islands are designed as national parks) and residents. The aim of this was to collect testimonies, photographic and video footage evidence of the extent of the run-up on the islands.

3 Results

3.1 Run-up heights

Table 1 shows the tsunami run-up heights measured in this survey, and Fig. 1 the locations of the points surveyed, together with the results of other surveys around the coastline of Java and Sumatra (Takabatake et al. 2019).

As shown in Fig. 1, the maximum run-up heights in Rakata island were 46.8 and 49.4 m. As this island was much higher than the others surrounding it, with steep slopes facing Anak Krakatau, it was not overtopped (see Fig. 2a and b). Tsunami heights were measured according to the line of vegetation remaining along the slope. Many rocks (of various sizes, some of them more than 1 m in diameter) were found on the beach of this island, though it was not clear when and how they had arrived there. The maximum measured run-up in Kecil island (local name: Panjang island) was 82.5 m, and parts of the island were actually overtopped (according to key informant interviews, see also Fig. 2c and d). Many of the vegetation in the islands was dead, due to the seawater overtopping them and the consequences of volcanic ash fall. According to the key informant interviews, although the island had a small jetty used for tourists visiting Anak Krakatau, this structure was completely washed away as a result of the tsunami. In Sertung island the maximum run-up was 39.9 m (see Fig. 2e), which was measured according to the damage of the vegetation. At the time of the survey much of Anak Krakatau had disappeared (see Fig. 2f).

Table 1: Measured tsunami run-up heights.

No	Place	Latitude (S)	Longitude (E)	Height (m)
1	Rakata island	6° 08’ 45.49”	105° 25’ 40.53”	46.8
2	Rakata island	6° 08’ 45.64”	105° 25’ 39.92”	49.4
3	Panjang island	6° 05’ 58.93”	105° 27’ 04.23”	82.3
4	Panjang island	6° 05’ 14.64”	105° 27’ 07.20”	82.5
5	Sertung island	6° 06’ 30.96”	105° 22’ 07.61”	39.9

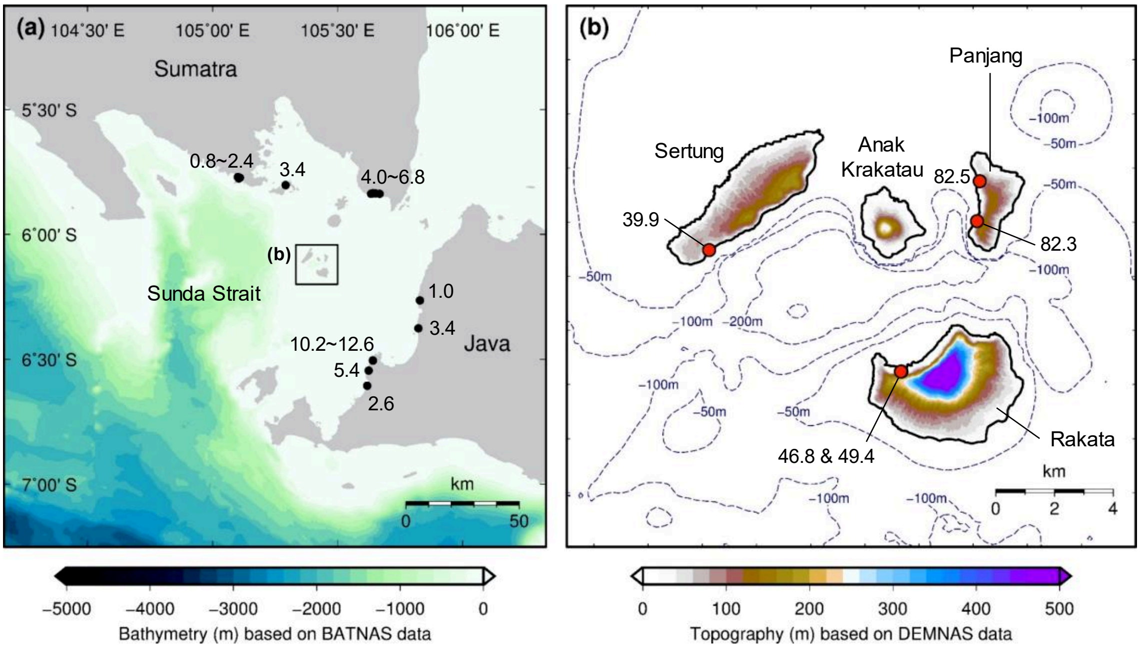
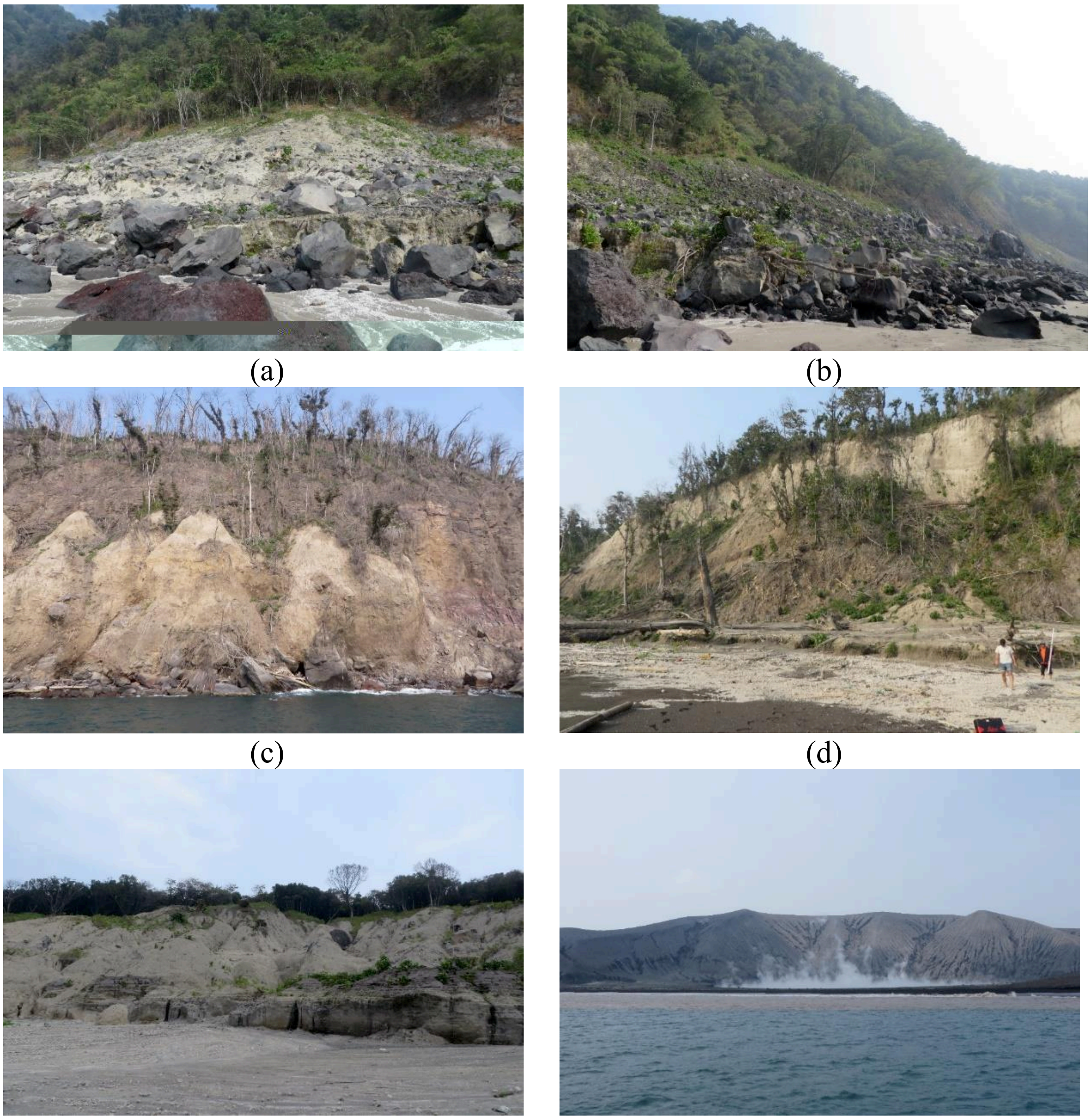


Figure 1: Maps of the area surveyed. Bathymetry and topography are based on BATNAS (resolution: 6-arcsecond) and DEMNAS (resolution: 0.27-arcsecond) data of Badan Informasi Geospasial (BIG, 2018b Geospatial Information Agency of Indonesia), respectively. (a) tsunami inundation and run-up heights measured by Takabatake et al. (2019). (b) tsunami run-up heights measured by the authors on three surrounding islands around Anak Krakatau.



(a) (b) (c) (d) (e) (f)

Figure 2: (a) Survey points. (a) Run-up survey point in Rakata island (No. 1 in Table 1), (b) Run-up survey point in Rakata island (No. 2 in Table 1), (c) Run-up survey point in Panjang island (No. 3 in Table 1), (d) Run-up survey point in Panjang island (No. 4 in Table 1), (e) Run-up survey point in Sertung island (No. 5 in Table 1), (f) Collapsed area in Anak Krakatau.

3.2 Bathymetry

Fig. 3 shows the interpolated contour lines obtained from the bathymetric surveys that were carried out. The bathymetry around the islands is rather complex, probably as a consequence of the dramatic disappearance of the former Krakatau island in the 19th century. Generally speaking, it is characterized by being fairly deep (with depths of around 200 m) to the southwest of Anak Krakatau. The channel between Panjang and Rakata towards the east is also deep (150-200 m), while the bathymetry to the north is only 25 to 50 metres in depth.

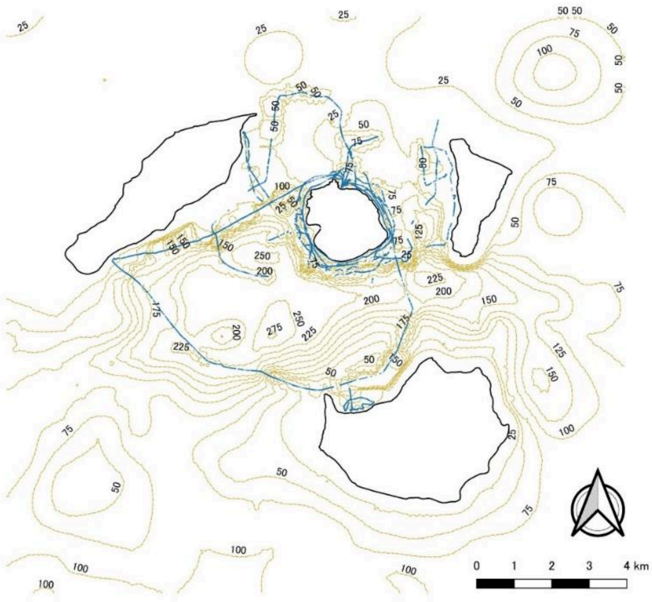


Figure 3: Bathymetric surveys conducted around the Krakatau islands. Continuous blue lines show the track of the two survey boats.

3.3 Volume of the collapsed slope

The aerial photographs obtained using the UAV were stitched together to form a map of the surface of the island at the time of the survey (see Fig. 4). From these images a Digital Elevation Model (DEM) was obtained, with Fig. 5 showing the elevation of the island before (Fig. 5a-c) and after the survey (Fig. 5d). Figure 6 shows the two transects indicated in Fig. 5, which highlights how almost the entire island collapsed into the sea.

The difference between the former and present day DEMs allowed the authors to calculate the volume of the material that was displaced by the eruption (which formed the landslide that generated the tsunami), see Table 2. According to this, between 0.286 and 0.574 km^3 of material was displaced by the flank collapse.

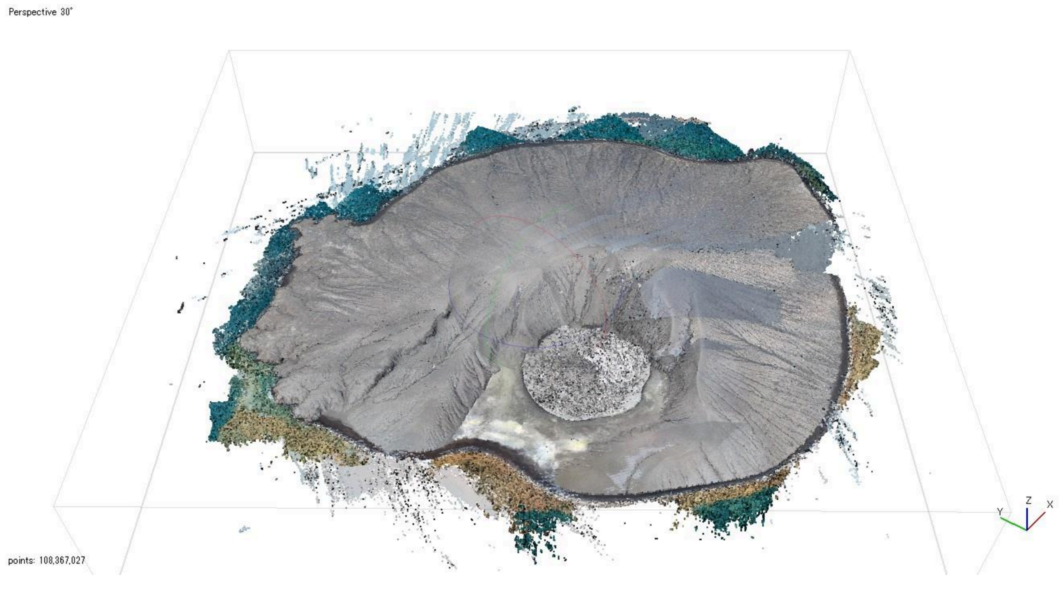


Figure 4: Stitched map of island from drone photography.

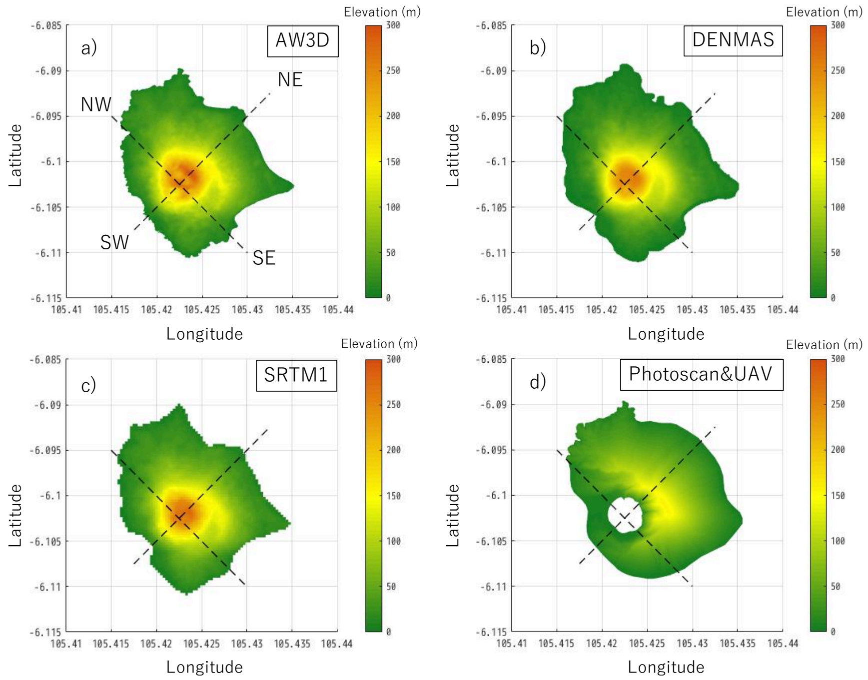


Figure 5: Digital Elevation Model (DEM) of the islands. (a) Top left: AW3D data. (b) Top right: DENMAS data. (c) Bottom left: SRTM data. (d) Bottom right: Present survey (Photoscan & UAV data, 90-percentile case). The SW-NE and NW-SE vertical transect lines indicated are shown in Figure 6.

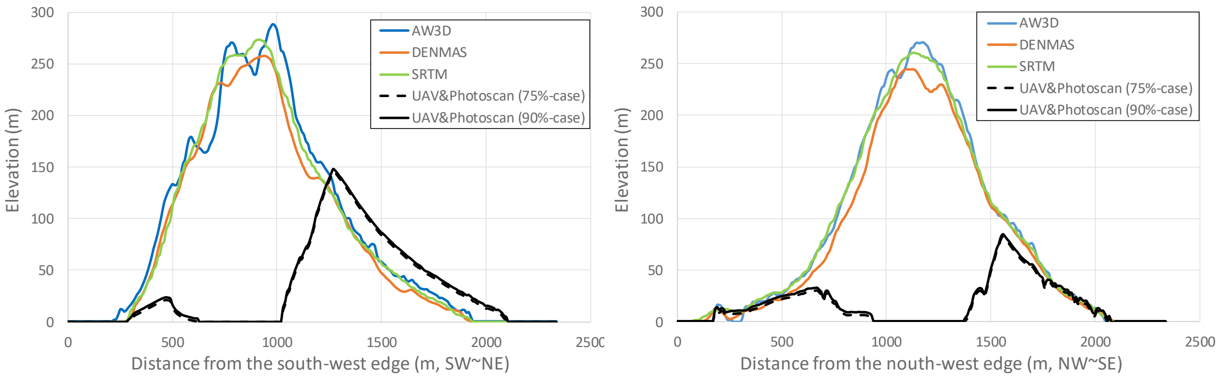


Figure 6: Transects of flank of Anak Krakatau, showing the historical evolution over time and the profile after the 2018 volcanic eruption (from DEM data). The location of the transects is given in Fig. 5. AW3D, DENMAS and SRTM represent the data available prior to the tsunami, with UAV data representing the authors' own surveys.

Table 2: Calculated volume of the material displaced by the eruption.

Data name	Horizontal resolution	Volume (km^3)	Top height (m)	Acquisition period
AW3D	2.5 m	0.18426	292	During from 2006 to 2011
SRTM	1 arc sec (≈30 m)	0.18184	277	February 2000
DEMNAS	0.27 arc sec (≈8 m)	0.16327	260	After 2006
UAV&Photoscan (75%-case)	0.22 m	0.12690	165	17th August 2019
UAV&Photoscan (90%-case)	0.22 m	0.13471	168	17th August 2019

3.4 Perimeter survey of the island

The 360˚ degree panoramic videos produced as part of this survey can be found on Vimeo (https://vimeo.com/showcase/6851365) and Hatch research blog (http://www.thehatch.tv/anak-krakatau/).

The *Anak Krakatau - Aerial 1 - 7* 360 Films were shot on a Nikon KeyMission 360 and allow the viewer to interact with the film and view the environment in 360 degrees. Unfortunately, the visibility of the underwater 360 film was less than one metre, given the large amount of suspended particles in the water column. Hence, none of this footage rendered anything of interest and are not included in the links given above.

There are two Anak Krakatau aerial UAV (Drone shots) that give the viewer a sense of location of the overhead terrain. From the films *001 - 012 Handheld* it is possible to obtain a visual sense of the run-up heights and loss of vegetation in the surrounding islands.

Additionally, the authors collected a number of videos of the event from some of the officers stationed in the islands. These *001 to 011_Guard* films are also included in this vimeo showcase, showing a range of eruptions from Anak Krakatau as the event was unfolding. There are a number of photographs also provided on the Hatch blog that were taken at the same time of filming, both from the guards and during the field survey.

4 Discussion

The measured run-up heights shown in Fig. 1 correlate well with the results of Grilli et al. (2019), who correctly identified that high-run ups would take place along Sertung and Rakata (they identified that the runup would be at least 45 m on the directly exposed steep shores of those islands, with 39.9 m being measured in the present survey along Sertung). However, Grilli et al. (2019) failed to reproduce the run-ups of Kecil (Panjang island), where the interviews with local officials and evidence on the ground (see Fig. 2a) indicate the island was overtopped. The authors measured run-up as high as 60-80 m, whereas Grilli et al. (2019) indicate that refraction around the volcano would result on run-ups of 15-25 m. At the southern side of Palau Sertung Borrero et al. (2020) report run-up heights of just around 50 m, raising to over 80 m. The authors only surveyed one point here, given that further north those interviewed indicated that the wave went over the island (thus it is not clear whether actually reporting the run-up height would be a good measure of this value). In the area of Rakata surveyed by the authors Borrero et al. (2020) indicate run-ups of 60 m, though they reported difficulty in obtaining results from Panjang.

Then, the authors analysed and try to estimate the volume of material that was lost during the eruption, which was estimated at 0.286-0.574 km^3 (which compares to the range of 0.22-0.30 km^3 estimated by Grilli et al. (2019), and could at least partly indicate the difference in run-up heights).

The field results have important implications for the simulation of tsunamis that could be caused by the future flank collapses of Anak Krakatau, and the importance of source directionality (i.e. the primary direction of the propagation of the tsunami as it propagates over the ocean). Takabatake et al. (2019) and TDMRC (2019) reported how the 2018 event caused relatively higher inundation and run-up heights in the north-north-eastern direction from Anak Krakatau (i.e., Central Waymuli–Kahai Beach), with a maximum surveyed run-up height of 6.8 m. In Java island, significantly higher inundation and run-up heights were measured at Cipenyu Beach (Pandeglang Regency), located to the south-south-eastern direction from Anak Krakatau, with over 10 m inundation and run-up heights being recorded. Essentially, the tsunami generated by the flank collapse of Anak Krakatau was partially blocked by the island around it (with, for example, Sertung island preventing the propagation of the tsunami towards Sinar Agung and Bandung Jaya).

This tsunami was generated in shallow water, and would have had a short wavelength than subduction fault tsunamis (Takabatake et al., 2020). The fact that the bathymetry was rather deep (over 200 m) in the southwest direction from Anak Krakatau would have helped the tsunami wave propagate in this direction away from the islands of Sumatra and Java, which can explain why inundation heights in the populated coastline in these islands was limited, see Fig. 1). However, the opening is rather large in this direction, which would have helped the tsunami wave energy disperse into the wider ocean.

While the main flank collapse appears to have been towards the south/south-west, the tsunami would have reflected off Rakata island towards the north. There is also the possibility that part of the volcanic collapse would have been towards the north (or other directions), explaining the considerable run-up in the other islands in the group. However, the bathymetry to the north of this group of islands is relatively shallow (around ~25 m in most area). This would have hindered propagation (due to a reduced flow rate due to the low celerity of the tsunami). The high density of the tsunami wave would have resulted in the tsunami growing in height, possibly causing some localized wave-breaking (though this last effect would have been minor). The worst inundation heights recorded by Takabatake et al (2018) were in western Java, which would have been facilitated by the slightly deeper bathymetry between Panjang and Rakata. However, far more important than the bathymetry is the effect of the shielding provided by the islands themselves, which would have reflected much of the wave energy and contained it within the inside of the archipelago. Also, the possibility that in such complex bathymetry the tsunami could have generated edge waves remains a (speculative) possibility, as has been indicated by research conducted on the characteristics of the 2011 Tohoku Earthquake and Tsunami in some areas (Koyano et al., 2020).

There were considerable challenges and limitations involved in this field survey. First of all, it took place months after the actual the flank collapse, meaning that by then some vegetation had regrown, and the authors could only obtain a lower limit of the possible run-ups that took place. In some cases, these measurements were based on long distance estimates, given that it was physically impossible to climb the steep side of the mountains (which are uninhabited).

The bathymetry measurements that were carried out can provide a rough indication of the overall bathymetry in the area. However, there were very clear and abrupt changes in bathymetry in short distances, indicating the presence of very steep underwater cliffs and rough edges. To obtain a full picture it would probably be necessary to conduct multi-beam measurements and spend considerable time mapping the area. Nevertheless, the data obtained can provide modellers with a better estimation than previously existing maps.

It should be noted that ground control points (GCPs) were not employed, and thus a precise validation of the ground elevation between the DEM and the actual topography were not carried out (it took the authors four hours to climb to the top of Anak Krakatau, and there was the risk of further volcanic eruptions). This may lead to some error, and explain the range of collapse volumes reported previous studies. Nevertheless, the maximum height for the 75- and 90-cases was 165 m and 168 m, which was in good agreement with a maximum height of 157 m reported in LCDV (2015). It should also be noted that the estimated volume of frank collapse is the accumulated change from the start of the event to the survey date (i.e. around 8 months). Williams et al. (2019) pointed out the possibility that the volume of the loss that initially occurred and the generated tsunamis could have been smaller.

In light of the data presented here further numerical modelling is needed to fully clarify this event. Takabatake et al. (2019) indicated how local residents reported two waves (separated by between 2-5 min), with the second wave being higher than the first. This would indicate a short wavelength, which would make this similar to the 2015 Taan Fiord tsunami (Higman et al. 2018) and the 2018 Palu tsunami (Takagi et al. 2019; Mikami et al. 2019). The 2018 event was clearly smaller in scale than the 1883 eruption of Krakatau, where tsunami heights of 15-22 were recorded in Sumatra island and run-up heights of 35 m in western Java (Symons 1888; Pararas-Carayannis 2003). However, it is also interesting to note that the tsunami period and wavelength (estimated to be 5 minutes and 7 kilometres, respectively), were similar to those of the present event. This would indicate the need to make a clear distinction between earthquake and landslide generation mechanisms regarding the resulting tsunami wave periods.

5 Conclusions

The authors surveyed the Krakatau group of islands with the intention of clarifying the run-up heights that took place after the 2018 Sunda Straight tsunami, and documented the current situation of the islands. Run-up heights of at least 82.5 m, 49.4 m and 39.9 m, were measured along Panjang, Rakata and Sertung islands, respectively. The high run-ups measured along Panjang island were corroborated through visual observations of the erosion caused by the overtopping tsunami waves and key informant interviews, and were intriguing given the expected source directionality due to the flank collapse of Anak Krakatau (towards the SW). The shelter effect given by the islands helped to explain the variation in wave inundation and run-up patterns along Sumatra and Java island reported in other field surveys.

Using DEM of Anak Krakatau before and after the eruptions and tsunami, the authors could calculate the volume of flank collapse on December 2018, which was estimated to be 0.286-0.574 km^3. Furthermore, the authors performed new bathymetric measurements around Anak Krakatau island, which will provide valuable input for tsunami generation and propagation simulations. Being able to obtain accurate results from such simulations is crucial for practicing engineers and disaster risk managers to be able to formulate adequate countermeasures and design infrastructure that can withstand the effects of tsunamis.

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Author contributions (CRediT)

ME: Fieldwork, Methodology, Writing-original draft. TT: Fieldwork, Methodology, Manuscript draft review and editing. HA: Fieldwork, Logistics. TM: Fieldwork, Methodology, Manuscript draft review and editing. RN: Fieldwork, Methodology, DEM analysis. MG: Fieldwork, Key informant interviews. SP: Fieldwork, Bathymetry surveys. YN: Fieldwork, Bathymetry Interpolation and Analysis. NI: Fieldwork, Analysis. CC: Visualization, Video Image Analysis. KO: DEM Analysis. TS: Project Planning, Methodology, Funding Acquisition, Project Administration, Manuscript Draft Review.

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