Study of Bathymetry and Seabed Morphology Changes Around Anak Krakatau Waters of 2018 Post-Eruption

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Abstract. Anak Krakatau is an active volcanic mountain located in the Sunda Strait, Indonesia. On December 22, 2018, this mountain erupted and the flank collapses off into the water. This changes the bathymetry and morphology of the seabed around the waters of Anak Krakatau volcano. This study uses bathymetry data surrounding the Anak Krakatau waters from the Indonesian Navy Hydrographic and Oceanographic Center (PUSHIDROSAL) in 2016 and 2019. The data were obtained by survey using Echosounder Multibeam System MBES EM2040 and EM302. By means of surface analysis method (hillshade), the data were process to observe the bathymetry and seabed morphology changes around the Anak Krakatau volcano waters by the eruption. The results of bathymetry data processing show a depth change of about 25 m, with the lowest value in 2016 ranging from -250,328 m and in 2019 ranging from -226.12 m. The average value of the slope of the seabed in 2016 was 5.31° and 4.98° in 2019.

1. Introduction
Krakatau is an active volcanic archipelago located in the Sunda Strait, between the islands of Java and Sumatra. In 1883 this ancient mountain erupted and formed a caldera. This eruption is considered as the most notable eruption, it because led a destructive tsunami that killing 36,000 people [1]. About more than 45 years after the catastrophe event in 1883, or to be precise in 1928, a volcano known as Anak Krakatau emerged from the same location as Krakatoa volcano. Most studies of this volcanic complex deal primarily with the famous 1883 eruption of Krakatoa [2][3].

Between 1928 and 1930, the Anak Krakatau volcano receded and reappeared three times until it became permanently independent above sea level. This volcano is a stratovolcano, and was built by alternating layers of lava and pyroclastics that have been erupting since the 1930s [4]. In 1959, a 152 m high hyaloclastic tuff ring was developed [5]. Anak Krakatau is an active volcano which increases in height every year, reaching a height of more than 300m [6].

Located in a volcanic complex, the magmatic activity in Anak Krakatau is thought to be controlled by the activation of the North West–South East trending fault system [7]. This active volcano has frequent eruptions of approximately once every one or two years. Over the last decade, Anak Krakatau erupted from October 2007 to August 2008 after a period of silence lasting for 6 years. During this eruption, a new crater formed on the southwest flank of the volcano just below the main crater, producing plumes of ash as well as lava flows. Moreover, during its evolution, Anak Krakatau experienced periods of intense activity with important eruptions in 1883, 1929, 2007, 2008 and 2018 [2][3][7].

The activity in Anak Krakatau is a consequence of its location at the intersection of an active fault and a north-south trending volcanic route in the Sunda Strait [8]. This volcano is in the transition zone...
between the frontal subduction of the Indo-Australian plate under Java and oblique subduction under Sumatra [9][10][11][12]. The Sunda Strait is a transition zone from the Sumatran trough (oblique subduction) to the Java trough (nearly frontal subduction). On December 22, 2018, Anak Krakatau volcano erupted and the flank collapses off into the water. This altered the bathymetry and morphology of the seabed around the waters of Anak Krakatau volcano.

Depth information is obtained through measurements using underwater acoustic technology equipped with sensors (transducers) that function to convert electrical signals into sound signals [13]. The sound signal emitted into the water column is capable of detecting underwater objects, then the object reflects the sound and transmits it back to the receiver. The acoustic system is very effective in exploring the underwater environment [14].

One of the acoustic technologies used to measure the depth of a waters and detect the presence of underwater objects is multibeam echosounder (MBES). MBES is an acoustic instrument that has the working principle of being able to emit many beams in one signal beam with a beam pattern that extends and crosses the ship's hull. Each beam gets one depth point and will form a topographical profile of the waters if all the depth points are connected to each other [15].

In this study, the topographic information of the seabed before and after the eruption analyzed is the contours and path profile. The contours are analyzed to identify changes in the topography of the seafloor. While the path profile is analyzed to provide an overview of the underwater topography changes that occur.

2. Material and Method

2.1. Study Area

The study area in this research is the waters around Anak Krakatau volcano in the Sunda Strait.

Anak Krakatau is a volcanic island located at the center of the Krakatau complex along the volcanic arc on the eastern N20, which extends from Mount Rajabasa to Panaitan Island, including the Krakatau
Islands [8][17]. The Krakatoa complex consists of four islands; Sertung, Panjang, Rakata and Anak Krakatau, together with the underwater caldera, are remnants of the 1883 Krakatau eruption, which have been studied by several authors [19][20][21][22][17][23][24]. The first three islands are the remains of the caldera collapse after the Krakatau eruption in 1883.

2.2. Method
The data of this research are secondary data of the Echosounder Multibeam System or MBES type EM2040 and EM302 with a resolution of 250m in 2016 and 2019 at the Anak Krakatau volcano waters, Sunda Strait. The data was obtained through a survey of the KRI Spica-934 belonging to the Indonesian Navy Hydrographic and Oceanographic Center (PUSHIDROSAL).

Hillshade is a method to produce maps that have a high level of sharpness in visualizing a relief from the surface [15]. Topographic visualization is clear and an invisible elevation pattern can be generated using this method. So that the bottom topography of the waters around Anak Krakatau volcano can be seen clearly using this method. The path profile of the seabed is obtained by generating a line of intersection on bathymetric contour map from the results of processing bathymetric data. The area for the value of the average sea slope is formed out of this line.

3. Result and Discussion

3.1. Contour Analysis
The previous studies, there is a deep caldera southwest of Anak Krakatau, and a steep seafloor slope close to the island where it changes from zero at the coast, to 250 m depths within a 750 m lateral distance. The subsea mass erosion deposits suggest that flank collapse is typical of frontal compressional fault erosion, triggered by critical instability due to ongoing volcanic activity. Erosion margins are identified by the smooth seafloor surface area which is interpreted as debris flow resulting from the placement of volcanic debris slides [25].

Bathymetry around the Krakatau Island complex in 2016 has an average depth of 30 - 90 m which is shallow water. Meanwhile, the 1883 caldera area in the southwest of Anak Krakatau volcano has a depth between 230 - 250 m, which is represented by a dark blue-purple color. This area has the lowest depth of about 250,328 m below sea level. Precisely at coordinates X 545941.6196021811 and Y 9323740.3477458972. In 2019 the bathymetry around the Krakatau Island complex has an average depth of almost the same as in 2016 which is between 30 - 90 m. And for the 1883 caldera area in the southwest part of Anak Krakatau volcano has a depth between 210 - 220 m, with the lowest depth of about 226.12 m below sea level at coordinates X 543146.8248319178 and Y 9325475.024754361. This is slightly different from previous studies which stated the maximum depth in 1883 before the disaster was 246 below sea level. Currently, the maximum depth has become shallower to 215 below sea level due to abundant volcanic material in the southwest area, giving an average deposit thickness of about 31 m [26]. This can occur due to differences in data types and resolutions used.

In the middle of the caldera at 2016 bathymetry map, there was a mound with a height of about 13 m. But in 2019 this mound is nowhere to be seen. This is due to the material from the collapsed side of Anak Krakatau volcano that enters the water body and creates siltation around the 1883 caldera area, so the dune in 2016 was covered. On the other hand, from the 2019 Bathymetry map, it can be seen that the collapse of the mountain side moved towards the southwest from the mountain side which resulted new mounds with a height of about 60 - 75 m. Previous research also stated that the discovery of sediment mounds more than 50 m thick after the 2018 eruption of Mount Anal Krakatau [27].
Figure 2. Bathymetry map around Anak Krakatau volcano at the Sunda Strait waters in 2016

Figure 3. Bathymetry map around Anak Krakatau volcano at the Sunda Strait in 2019
3.2. Path Profile Analysis

**Figure 4.** Cross-sectional image taken for path profile analysis on the 2016 bathymetric map.

**Figure 5.** Cross-sectional image taken for path profile analysis on the 2019 bathymetric map.

**Figure 6.** The path profile results are based on the cross section used in the 2016 bathymetry map.

**Figure 7.** The path profile results are based on the cross section used in the 2019 bathymetry map.
Anak Krakatau volcano is on the right side of the path profile picture, shown in Figures 6 and 7. In the cross-section AB there is a slight siltation of about 3-4 m. In the cross section of the CD there is silting of about 20 m. In the cross section of the EF, there is a shallowing of about 22 m and shows a 73 m high mound which is about 1.5 km from the mainland. This is reinforced by previous research which stated that the extent of underwater mass landslide deposits, from the bathymetric boundary of the rough seabed, is about 1.5 km southwest of Anak Krakatau. The area of subsea mass avalanche deposits, or lump facies in the southwest region, is approximately 7.02 ± 0.21 km [25]. In the cross section of GH, there is a significant difference, the material on the Anak Krakatau mountain side moves up to a distance of 3.5 km. The siltation that occurs is about 23 m. In the cross-section of IJ, the mound in 2016 is seen moving to the southwest which makes 16 m shallowing around the IJ area.

### Table 1. The average slope value of the cross-section in 2016.

| Line | Length (km) | Minimum Elevation (m) | Average Slope (°) |
|------|-------------|-----------------------|-------------------|
| AB   | 5.63        | -214.255              | 2.87              |
| CD   | 6.772       | -243.887              | 2.91              |
| EF   | 7.309       | -247.838              | 2.77              |
| GH   | 8.052       | -248.886              | 2.56              |
| IJ   | 8.941       | -232.585              | 2.97              |

From the cross-sectional lines taken, the GH line has the smallest average slope in 2016 and 2019. And the IJ line has the largest average slope value in 2016 and the AB line in 2019.

### Table 2. The average slope value of the cross-section in 2019.

| Line | Length (km) | Minimum Elevation (m) | Average Slope (°) |
|------|-------------|-----------------------|-------------------|
| AB   | 5.63        | -217.312              | 3.14              |
| CD   | 6.772       | -223.711              | 2.84              |
| EF   | 7.309       | -225.261              | 2.74              |
| GH   | 8.052       | -225.444              | 2.54              |
| IJ   | 8.941       | -216.958              | 3.04              |

### 4. Conclusion

The results of bathymetry data processing show a depth change of about 25 m, with the lowest value in 2016 ranging from -250.328 m at coordinates X 545941,6196021811, Y 9323740,3477458972 and in 2019 ranging from -226.12 m at coordinates X 543146,8248319178, Y 9325475,0247543361. After the eruption, new mounds appeared up to 73 m high on the seabed. Eruption material from the side of Anak Krakatau volcano changes the morphology of the seabed. The slope of the area from around the cross-sectional line also changes. The average value of the slope of the seabed in 2016 was 5.31° and 4.98° in 2019. Changes in depth and morphology on the seabed can affect shipping activities. According to the Indonesian Navy's Center for Hydrography and Oceanography (PUSHIDROSAL) map number 71A, this area is classified as a dangerous area. However, the depth and morphology changes information still needed for shipping safety.
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