The Tsunami Model of Mount Anak Krakatau Landslide in 2018 and Its Future Potential Hazard to the Coastal Infrastructures in Sunda Strait

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Abstract. This study is motivated by the tsunami event caused by Mount Anak Krakatau flank collapse on 22nd December 2018 which affected vital areas in Southern Sumatera and Western Java. A tsunami simulation will be carried out by using a 2D Non-Linear Shallow Water Equation Model to estimate the volume of the initial source as well as their tsunami mode at shores. Various scenarios of initial water volume replicating the tsunami source were applied, where the tsunami heights and their periods reach shores are validated with mareogram data at four Stations. The fact that the remaining materials of Mount Anak Krakatau after the 2018 event are still potential to generate a hazardous tsunami in the future and threaten the coastal infrastructures along the coastal Sunda Strait area. In this study, the validated parameters resulting from the 2018 event above are applied to model of the plausible worst scenario where the entire of the flank of Mount Anak Krakatau potentially collapses in the future. The study is important to estimate the tsunami hazard potential in the future that obviously influencing major activities and life's in vital industrial-urban area in Southern Sumatera and Western Java.

Keywords: coastal infrastructures, numerical model, Mount of Anak Krakatau, tsunami heights, sensitivity test.

1. Introduction
During period years of 1600 to 1999, 105 tsunami events hit Indonesia region with 90% events caused by earthquake, 8% by volcanic eruption and 1% by landslide [1]. In total, those tsunamis caused 54,100 fatalities and 43,000 of them due to volcanic tsunami. Even tsunami occurred frequently in Indonesian coastal, the natural mechanism and characteristic are still not well known [1]. The tsunami that generated by landslide is more catastrophic due to it may arrive without any seismic warnings [2].

The largest volcanic event that caused tsunami was tsunami Krakatau at 27th August 1883 which produced by hydro-volcanic explosion and the associated shock wave and pyroclastic flows [3]. This tsunami killed almost 36,000 people around Sunda Strait. The tsunami height at Lampung was 21.9 m,
24.4 m at Kalianda, and 41 m at Merak, Banten [4]. The potential tsunami Anak Krakatau could be produced by flank collapse due to the steep wall of caldera from 1883 event remain unstable [5].

On the 22nd December 2018 at 21:30 local time (UTC+7), tsunami wave that generated by Mount Anak Krakatau (AK) in the Sunda Strait hit coastal along Java and Sumatera. The tsunami caused 437 fatalities, 10 persons lost, and 31,943 injured. According to satellite photographs and radar images of Mount AK, this tsunami was generated by flank collapse [6]. The estimated volume range of submarine collapse geometries result in primary landslide is 0.22-0.3 km³ [7]. Previous studies related to volume of flank collapse of AK in 2018 event are shown in Table 1 below.

Table 1. The previous studies related to tsunami Sunda Strait at 22nd December 2018 [5, 7-8].

| Volume Flank Collapse | Tsunami Height | Tsunami Travel Time |
|-----------------------|----------------|---------------------|
| 0.28 km³              | 1.5 m (Merak)  | 35-45 min.          |
|                       | 3.4 m (Labuhan)|                    |
| 0.22-0.3 km³          | 13 m (Southeast Sumatera and West Java) | 30 min. |
| ~0.1 km³              | 0.3 - 3.4 m   | 24-37 min.          |

The leftover volume of Mount AK will be a potential tsunami that might generate by any possible mechanism like volcanic activity, blasting, or flank collapse since it is still an active volcano. Mount AK that located in Sunda Strait will influence human activities and infrastructures in southern Sumatera and Western Java [4] [5]. It is necessary to observe the worst potential of tsunami AK and its implication to those infrastructures and human activity along southern Sumatera and Southern Java since Tsunami will cause a huge damage in infrastructures and human’s life [9]. There are three parts of tsunami generated by landslide phenomena; energy transfer from slide motion to water motion, wave propagation, and the runups along the coastal [10]. It is also proven that the landslide acceleration influences the initial tsunami elevation [11].

The aim of this study is to estimate the volume of Mount AK flank collapse at 22nd December 2018 tsunami event by comparing-analysing pre-post event of satellite images and DEM data; validating the tsunami mode at shores resulting from various volume-shape of initial sources with mareogram data recorded at tide station; and estimate the volume of leftover of AK and use it as the source of numerical model for potential worst scenario tsunami AK in future. The distribution of wave heights of worst potential tsunami and their travel times at several infrastructures along Java and Sumatera will be estimated.

2. Data and Method

2.1 Scenarios and Domain Model Used for Tsunami Simulation of AK 22nd December 2018 Event
There are mareogram data from Indonesia Geospatial Information Agency (BIG) that situated at Serang, Ciwandan, Kota Agung, and Pelabuhan Panjang (Figure 1). Those stations recorded sea level when tsunami 22nd December 2018 at Sunda Strait occurred (Figure 2 and Table 2). This mareogram data will be used to validate the numerical model. Figure 2 shows mareogram data that the tide are already removed.
Figure 1. The location of stations data (black dots).

Serang (105.841E, 6.1893S)  Ciwandan (105.953E, 6.0176S)

Agung City (104.619E, 5.5003S)  Panjang Port (105.319E, 5.4713S)

Figure 2. Graphs of mareogram data at 4 stations.

Table 2. Tsunami wave height and estimated tsunami time arrival at 4 stations.

|                  | Serang        | Ciwandan      | Agung City    | Panjang Port |
|------------------|---------------|---------------|---------------|--------------|
| **Tsunami Wave Height** | -1.3 m to 1.5 m | -0.5 m to 0.7 m | -0.4 m to 0.5 m | -0.5 m to 0.6 m |
| **Estimated Time Arrival (UTC+7)** | 21:30         | 21:36         | 21:40         | 22:03        |

To estimate the volume of the initial source as well as their tsunami mode at shores, a tsunami simulation will be carried out using a 2D Non-Linear Shallow Water Equation Model [12]. Various scenarios of initial water volume replicating the tsunami source were applied (Table 3), where the tsunami heights and their periods reach shores are validated with mareogram. There are 4 steps to determine the scenario model as shown in Table 3. Those scenarios use different Manning number (0.020, 0.025, and 0.030), initial wave height (50 m to 250 m with interval 25 m & 50 m), and source shape (circle, oval, and arch) (Figure 3).
The 1\textsuperscript{st} and 2\textsuperscript{nd} steps were calculated to find the smallest deviation of NRMSD between mareogram data and model result. The parameter model’s variation is the initial wave height and Manning number. Further, after the initial wave height is determined, the 3\textsuperscript{rd} and 4\textsuperscript{th} steps were used to test the sensitivity of the various shapes. The grey scenario’s initial wave heights are the most similar with mareogram data. From total 22 scenarios, the 16\textsuperscript{th} scenario result has the smallest Normalized Root Mean Square Deviation (NRMSD) compared with mareogram data, which is the initial wave height is 175 m (or equal to 0.175 km\textsuperscript{3}) and the Manning number is 0.020. This scenario will be applied in numerical model.

### Table 3. Scenarios used for tsunami Anak Krakatau 22\textsuperscript{nd} December 2018 numerical model.

| Sc | Manning Initial Wave Height (m) | NRMSD |
|----|--------------------------------|-------|
| Sc1 | 50 | 0.36 |
| Sc2 | 100 | |
| Sc3 | 0.02 | |
| Sc4 | 200 | |
| Sc5 | 250 | |
| Sc6 | 50 | |
| Sc7 | 100 | |
| Sc8 | 0.025 | |
| Sc9 | 200 | |
| Sc10 | 250 | |
| Sc11 | 50 | |
| Sc12 | 100 | |
| Sc13 | 0.03 | |
| Sc14 | 200 | |
| Sc15 | 250 | |

| Sc | Manning Initial Wave Height (m) | NRMSD |
|----|--------------------------------|-------|
| Sc3 | 150 | 0.35 |
| Sc16 | 0.02 | |
| Sc17 | 175 | 0.34 |
| Sc4 | 200 | 0.37 |
| Sc8 | 150 | 0.35 |
| Sc18 | 0.025 | |
| Sc9 | 175 | 0.35 |
| Sc13 | 200 | 0.38 |
| Sc14 | 150 | 0.35 |

| Sc | Shape | NRMSD |
|----|-------|-------|
| Sc21 | Circle | 0.38 |
| Sc22 | Oval | 0.39 |
| Sc16 | Arch | 0.34 |

To obtain the tsunami arrival time, the best fit of NRMSD between tsunami mode from the model and tsunami mareogram data at stations are selected (Table 3). The time of initial sources are observed and compared with the seismic data from Cigerulis Station, Serang (Figure 4). From Figure 4, it is estimated that the flank collapse of Mount Anak Krakatau started from 13.56 UTC or 20.56 local time.

Seismic signal shown in Figure 4, is seismic record at Cigerulis Station, Banten, on 22\textsuperscript{nd} December 2018. The station situated approximately 55 km from the tsunami source. The period presented in this
seismic record is a crucial data before the flank collapse of AK fall and generated the tsunami around 20.26 local time. The signal characteristic in Figure 4 does not show a strong shear wave which means there are no shearing process due to slip phenomena. This phenomenon indicates that it was not a tectonic activity.

**Figure 4.** Seismic data at Station Cigeulis, Serang. The horizontal component is time in UTC, IA CGJI BHE is the east-west component, IA CGJI BHN is the north-south component, and IA CGJI BHZ is elevation [13].

The domain used in this study presented at Figure 4, including southern part of Sumatera and western part of Java. Table 4 shows the topography [14], bathymetry, and tidal data [15] used for the numerical model of tsunami AK 22nd December 2018.

**Figure 5.** Domain area for tsunami numerical model in Sunda Strait. The red box is where the initial source situated.

| Parameters                  | Data sources & grid size design |
|-----------------------------|---------------------------------|
| Topography                  | DEMNAS (grid size 100 m x 100 m) |
| Bathymetry                  | BATNAS (grid size 100 m x 100 m) |
| Mareogram data (for comparison) | Geospatial Information Agency (BIG) |

2.2 Numerical Model of Worst Potential Tsunami of AK

Based on DEM data analysis pre-post event, the total landslide material caused by AK 2018 was 0.08 – 0.1 km$^3$. From the model validation and the deviation of NRMSD (Table 3), it is estimated that the initial water volume is about 0.175 km$^3$. It can be assumed that the initial source of AK tsunami 2018 caused by material collapsed (0.08-0.1 km$^3$) and the remaining being presumably from the lateral blasting (0.095 – 0.075 km$^3$).
Figure 6. a. Mount Anak Krakatau contour after landslide December 2018 and b. The cross-section of Mount Anak Krakatau height after landslide December 2018.

The pre-collapse height of AK is about 335 m and post-collapse approximately 110 m [7]. From this data and the result of our numerical model, it can be conclude that the whole leftover AK causing tsunami is about 0.210 km$^3$. There are several assumptions of initial source that will be used for modelling the potential worst case of AK since the actual collapse mechanism is still unknown:

a. Approximately 30% materials becoming ash (0.06 km$^3$) and 70% (0.150 km$^3$) materials causing tsunami.

b. Initial water volume that used in model is 0.15 km$^3$ from material collapse and 0.15 km$^3$ from blasting.

c. 0.3 km$^3$ initial water volume will be used to measure the potential worst case of AK.

2.3 The Calculation of Inundation Distance and Run-Up Height Tsunami

The inundation distance (L) and the run-up height of tsunami (R) can be estimated by using the equations below [16], giving:

$$L = \frac{3a}{2} \ln \left( \frac{Ys}{aS_0} + 1 \right)$$

$$R = L S_0$$

With $a =$ roughness aperture, $Ys =$ shoreline wave-crest level, and $S_0 =$ uniform ground slope. We use the roughness aperture ($a$) of all observed area as undulating open ground and light building with value 100 m and 80 m, respectively. The uniform ground slope applied in this study was assumed 0.02 which means the slope is steep.

3. Result and Discussion

3.1. Obtaining Volume of Initial Water for Tsunami AK 2018 Simulation

After running the numerical models with 22nd different scenario of tsunami AK (Table 3) and compare them with marigram data in 4 stations (Figure 1), the 16th scenario has the best fit with field data with nRMSD 34%. Table 5 present the scenario chosen for tsunami AK 2018 simulation.
Table 5. Scenario chosen for tsunami AK 2018 simulation.

| Scenario Parameters | Value |
|---------------------|-------|
| Manning             | 0.02  |
| Volume (km$^3$)     | 0.175 |
| Initial wave height (m) | 175   |
| Shape               | Arch  |

At first, the sources used for tsunami model has 1 km$^2$ area, then 5 different height of initial water were applied to obtain the volume of initial water. The initial water volume presented the volume of water that caused by any mechanism of tsunami AK. The volume of slide material plays the most important role in generating tsunami landslide [17]. Figure 6 shows the tsunami wave height at 4 stations (Figure 1) with different volume of initial water (50 m, 100 m, 150 m, 175 m, 200 m, and 250 m). From the graphic, the tsunami mode is sensitive to volume of initial water tsunami AK. From the simulation we can conclude that the volume of initial water caused tsunami 2018 event approximately 0.175 km$^3$ (area size = 1 km$^2$ and the initial water height = 0.175 km). It is comparable with previous study which the volume is about 0.22 to 0.3 km$^3$ [7] and 0.1 km$^3$ [8].

![Graphs showing tsunami wave heights at various initial volumes for four stations: Serang, Ciwandan, Agung City, and Panjang Port.](image)

Figure 7. Tsunami height comparison between various initial volume and the marigram data.

The comparison between various initial shape (Figure 7.) and various initial heights (Figure 8.) by maintaining the volume of initial water volume (0.175 km$^3$) shows that the differences initial shape and initial height has no significant effect to tsunami mode. It is seen that all the graphics in 4 stations (Serang, Ciwandan, Kota Agung, and Pelabuhan Panjang) has similar tsunami wave height.
Figure 8. Tsunami height comparison between various initial shape (volume=0.175 km$^3$).

Figure 9. Tsunami height comparison between various initial shape (volume=0.175 km$^3$).
Figure 10. Tsunami height comparison between various initial height (volume = 0.75 km$^3$).

3.2 Maximum Tsunami Wave Height and Estimated Time Arrival

The maximum tsunami wave height based on simulation of tsunami AK 2018 by using scenario in Table 5 is shown in Figure 10. It is seen that the tsunami propagation mostly to the northwest and southeast of Mount AK. The highest tsunami height at southern Java hit Pandeglang about 6.8 meter while the maximum tsunami height at southern Sumatera hit Kalianda, 4.8 meter (Table 6.). According to previous study, the most catastrophic area was Kabupaten Pandeglang followed by Lampung Selatan and Serang [18]. In addition, based on field survey data the tsunami wave height at north-north east of AK was larger than 4 meters [19], so it is supporting our numerical model result.

Figure 11. Distribution of maximum tsunami wave height at domain model.
Table 6. Maximum tsunami wave height at several cities and regencies along Java and Sumatera.

| Cities/Regency | Western Java | Southern Sumatera |
|----------------|--------------|-------------------|
|                | Cilegon | Serang | Pandeglang | Tanggamus | Pesawaran | Bandar Lampung | Kalianda |
| Max. Wave Height (m) | 1.2     | 2.3     | 6.8        | 1.7       | 0.9       | 0.8            | 3.8     |
| Mean Wave Height (m)  | 0.4     | 1.1     | 1.1        | 0.4       | 0.6       | 0.6            | 0.7     |

Tsunami wave height at AK’s islands surroundings are illustrated in Figure 11, and the maximum and mean tsunami wave height presented in Table 7. Along Mount AK, the maximum tsunami wave is about 96 meter due to the location that near to the source (Figure 10) followed by Sertung Island (32.8 m), Rakata Island (32.2) and Panjang Island (22.8 m).

Figure 12. Illustration of distribution tsunami wave height along island surroundings.

Table 7. Maximum and mean tsunami wave height at AK surroundings.

|                  | AK      | Sertung Island | Panjang Island | Rakata Island |
|------------------|---------|----------------|----------------|---------------|
| Max. wave height (m) | 96.01   | 32.8           | 22.8           | 32.2          |
| Mean wave height (m) | 29.7    | 11.5           | 8.5            | 9.7           |

The seismic data at Station Cigeulis, Serang (Figure 3.) shows that the estimated time landslide occurred at Mount AK was 20:56 local time (UTC+7). The tsunami propagation time are presented in Figure 12. The contour shows tsunami propagation per-5 minute from source to the coastal along Java and Sumatera. The colour presented time in minute. Serang has the smallest tsunami travel time (35 minutes) followed by Kota Agung (41 minutes), Ciwandan (44 minutes) and Pelabuhan Panjang (67 minutes) (Table 8.). By calculating the tsunami travel time and estimated time of flank collapse from seismic data, the estimated tsunami time arrival at those stations (Table 8.) will be measured.

Table 8. Tsunami travel time and estimated tsunami arrival at 4 stations.

| Tide Sta.   | Tsunami Travel Time (min.) | Estimated Tsunami Arrival (UTC+7) |
|-------------|----------------------------|----------------------------------|
| Serang      | 35                         | 21:31                            |
| Ciwandan    | 44                         | 21:40                            |
| City Agung  | 41                         | 21:37                            |
| Panjang Port| 67                         | 22:03                            |
3.3 Simulation Tsunami Model for Potential Worst-Case Tsunami AK

The simulation of potential worst-case tsunami AK use the whole leftover volume of Mount Anak Krakatau as the tsunami source with several assumptions. Based on volume of existing AK, the remaining volume of AK after collapse in 2018 is 0.210 km$^3$. Initial wave volume used in the model is about 0.3 km$^3$ with 0.15 km$^3$ from material and 0.15 km$^3$ from blasting. Thirty percent (30%) of the whole material is assumed to be ash and the rest material (0.15 km$^3$) will caused the tsunami. The comparison of tsunami wave height at 4 stations between tsunami on Dec 2018 event and the potential tsunami of AK are presented in Figure 12 and Table 9. It is interesting to note that the tsunami wave height from potential worst-case simulation are 4 times larger than those in 2018 event (Table 9).

![Tsunami height at Serang](image)

![Tsunami Height at Ciwandan](image)

![Tsunami Height at Agung City](image)

![Tsunami Height at Panjang Port](image)

**Figure 13.** Comparison of tsunami wave height between tsunami December 2018 event and the potential worst-case tsunami of AK at four (4) stations.
Table 9. The maximum tsunami height at four (4) stations (the tsunami December 2018 event and the potential worst-case scenario).

| Tsunami Height Max (m) | Serang | Ciwandan | Agung City | Panjang Port |
|------------------------|--------|----------|------------|--------------|
| Potential Tsunami      | 6.5    | 2.5      | 1.2        | 1.4          |
| Dec 2018 event         | 1.3    | 0.6      | 0.3        | 0.3          |

From the simulation model, the distribution of tsunami wave height and its propagation were observed (Figure 13). There are nine (9) main areas observed including industrial area along north Banten and Way Pisang, tourism area, special economic zone in Tanjung Lesung and National Park at Ujung Kulon. It is seen from distribution of maximum tsunami wave height that the larger tsunami height located northwest and southeast of AK, similar with tsunami in December 2018 (Figure 13. a). The contour presented in Figure 13. b is the travel time of tsunami per-five minutes.

Figure 14. The maximum tsunami wave height and tsunami propagation distribution.

The highest tsunami wave hit Ujung Kulon National Park (~6 m) and Tanjung Lesung Special Economic Zone (~5 m) when in Teluk Kiluan, Teluk Lampung, Banten industrial area and Labuan power station tsunami wave height approximately 1 meter. Teluk Kiluan that situated near the source has the smallest tsunami time travel, about 26.5 minutes while in Way Pisang needs half an hour for tsunami to hit the shore (Table 10). The horizontal and vertical run up tsunami at nine (9) main area can be determined as presented in Table 10. The slope data are assumed 0.02 for all areas. The longest distance of run up tsunami located in Ujung Kulon National Park, about 182.1m (α=100) and 165.1 m (α=80) as well as the height tsunami run up (4.1 m and 3.7 m, respectively). This inundation data is necessary to estimate the tsunami evacuation and emergency planning [20].

The result of simulation potential worst-case tsunami in Sumatera shows that the highest tsunami height is about 8.5 m while in Java about 7 m. The island that hit by the highest tsunami height is Panjang Island, approximately 42 meters (Table 11). Six major industrial area along Java and Sumatera also observed including urban and tourism areas (Carita-Anyer, Canti-Kalianda, and Lampung-Teluk Betung), National Park Ujung Kulon, industrial areas along northeast Banten, and Tanjung Lesung Special Economic Zone (SEZ).
Table 10. The maximum tsunami wave height, tsunami travel time, and run-up at nine (9) main areas.

| Area                                             | Tsunami Height Max (meters) | Tsunami Travel Time (minutes) | Slope (So) | a(1) | a(2) | Run-up (meter) |
|--------------------------------------------------|-----------------------------|-------------------------------|------------|------|------|----------------|
| Tanggamus Industrial Maritime Area                | 0.3                         | 38.82                         | 0.02       | 100  | 80   | 26.72 0.53 26.18 0.52 |
| Way Pisang Industrial Area                        | 0.2                         | 90.05                         | 0.02       | 100  | 80   | 20.70 0.41 20.37 0.41 |
| Kiluan Bay (Tourism Area)                         | 1.01                        | 26.56                         | 0.02       | 100  | 80   | 61.72 1.23 59.09 1.18 |
| Teluk Lampung (Tourism Area)                      | 1.15                        | 69.5                          | 0.02       | 100  | 80   | 68.57 1.37 65.38 1.31 |
| Tanjung Lesung Special Economic Zone              | 4.7                         | 31.09                         | 0.02       | 100  | 80   | 182.19 3.64 165.1 3.30 |
| Ujung Kulon National Park                         | 5.9                         | 33.61                         | 0.02       | 100  | 80   | 207.47 4.15 186.5 3.73 |
| Banten Industrial Area                             | 1.1                         | 47.69                         | 0.02       | 100  | 80   | 69.13 1.38 65.90 1.32 |
| Labuan Power Station (PLTU)                        | 1.02                        | 45.7                          | 0.02       | 100  | 80   | 61.87 1.24 59.23 1.18 |

Table 11. The maximum tsunami wave height at Java, Sumatera, AK, and Islands surroundings.

| Max tsunami wave height (m) | Java | Sumatera | GAK | Rakata | Sertung | Panjang |
|-----------------------------|------|----------|-----|--------|---------|---------|
| Potential tsunami           | 7.04 | 8.55     | 100.00 | 28.98 | 38.12 | 42.25 |
| Tsunami Dec 2018            | 6.09 | 4.68     | 96.01 | 35.07 | 33.22 | 22.95 |

Table 12. The maximum tsunami wave height at six (6) main infrastructures along Java and Sumatera.

| Max tsunami wave height (m) | Carita | Kalianda | Betung Bay | Ujung Kulon | Banten Industrial Area | SEZ Tj Lesung |
|-----------------------------|--------|----------|------------|-------------|------------------------|--------------|
| Potential tsunami           | 3.34   | 4.85     | 1.78       | 6.37        | 1.95                   | 5.01         |
| Tsunami Dec 2018            | 3.03   | 3.87     | 0.67       | 3.89        | 1.32                   | 4.47         |

4. Conclusions

Our hypothetic model shows that the initial volume that has the best fit with mariogram is 0.175 km³. With the manning number used is 0.02 and initial source shape is arch. This scenario has the smallest nrmsd (34%) compared with another 21st scenario. Except the volume of initial sources, the changes in shape and initial height of sources are insensitive to tsunami mode at shores (at tide station). Our
simulation for tsunami 2018 event in Sunda Strait shows that the maximum tsunami wave height at western Java about 6.8 m in Pandeglang and at 3.8 m at southern Sumatera. The tsunami travel time along coastal of Java and Sumatera approximately 35-67 minutes after flank collapse. 

The simulation of potential worst case tsunami AK assumes that all the leftover volume of AK will causing tsunami (flank collapse and blasting). The estimated initial water volume after pre and post DEM analysis of AK is 0.3 km$^3$ (0.15 km$^3$ from material collapse and 0.15 km$^3$ from blasting). In this scenario, the tsunami wave height four (4) times larger than tsunami event during December 2018. Tsunami wave heights at several main areas along Java and Sumatera are between 0.39 m (Tanggamus) to 5.97 m (Ujung Kulon National Park) and its tsunami travel time ranging from 36.5 min (Teluk Kiluan Tourism Area) to 90 min (Industrial Area Way Pisang).

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