A numerical study of submarine–landslide–generated tsunami and its propagation in Majene, West Sulawesi

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Abstract. On 14th January 2021, there was a devastating earthquake (Mw 6.2) hit Mamuju and Majene, West Sulawesi, Indonesia at 18.28 UTC. According to National Disaster Management Authority, this event causes 84 casualties and 279 houses were damaged. The Sulawesi Island is situated in a very complex tectonic region, there are several thrusts and faults along the area such as Majene Thrust, Palu-Karo Thrust, Matano Fault, and Tolo Thrust that can lead to tectonic activities. One of the largest earthquakes was a 7.9 Mw in 1997 generated from North Sulawesi Megathrust that caused a catastrophic tsunami. Moreover, there were 9 tsunami events in the Makassar Strait from the year 1800 to 1999. In this research, three different scenarios of the tsunami in Majene were applied to obtain the tsunami elevation. Makassar Strait could be potentially generated tsunami wave from submarine landslides due to its steep bathymetry that will impact the coastline at Sulawesi and Kalimantan, so it is necessary to model the tsunami propagation using submarine landslide as the tsunami generation. The volume of submarine landslide had been used in tsunami submarine landslide modelling as an input. Those are included the height, width and length of the submarine landslide volume. Furthermore, the domain bathymetry was obtained from National Bathymetry (BatNas) with spacing grid of 300 m x 300 m. The submarine landslide coordinate is also needed as a source of tsunami at 2.98°S and 118.94°E. The slide angle and slope angle are also inputted in this modelling with three experimental volumes, namely 1 km$^3$, 0.8 km$^3$, and 0.5 km$^3$. This submarine landslide tsunami modelling used the Non-Hydrostatic WAVE Model (NHWAVE) method to obtain tsunami wave generation. The result from NHWAVE model will be used for initial elevation of tsunami wave propagation using the Fully Nonlinear Boussinesq wave model - Total Variation Diminishing (FUNWAVE - TVD) method. The highest initial tsunami elevation value at each observation point obtained from the NHWAVE model occurred at point 18 (the closest location to the earthquake source), which is around 0.4 – 1.2 m. The FUNWAVE simulation result is the tsunami wave propagation for 180 minutes later. In the 180th minute, the tsunami wave was still propagating towards the north of Sulawesi Island to the east of Kalimantan Island.

Keywords: submarine landslide, tsunami, Non-Hydrostatic WAVE Model, Fully Nonlinear Boussinesq wave model - Total Variation Diminishing

1. Introduction
The West Sulawesi, Indonesia, has a high potential of earthquake and tsunami. Since 1820, five catastrophic earthquakes happened in the West Sulawesi and some of them followed by a tsunami. These tsunami events occurred in 1820, 23rd February of 1969 (61 casualties), and 11th April 1976, while at 8th
January 1984 (2 casualties) and 15th January 2021 the earthquakes were not followed by a tsunami [1]. The main trigger mechanisms of tsunamis supposed to be earthquakes, submarine and subaerial mass wastings, volcanic activities, meteotsunamis and cosmic impacts [2]. However, submarine landslide has become dangerous because it creates a spontaneous tsunami and pose tsunami hazard to coastline since it often has a very large run-up height [3] and [4].

The latest tsunami landslide event near the area occurred at Palu City at 28th September 2018 and it started with a magnitude of Mw 7.5 earthquake. The earthquake triggered the landslide (with volume 0.78 km³) that appeared from coastal slope failure mechanism and caused a tsunami [5]. Previously, at Palu City, there was three tsunami events in 1927, 1938, and 1968 with tsunami elevation of 15, 3, and 10 m. In addition to that [6] stated that since 1990, there was 8.6% tsunami events in Indonesia that occurred in Makassar Strait with 1023 casualties. Makassar strait is also prone to landslide-tsunami. A-10 km³ to 650 km³-mass transport deposits at Makassar Strait could be potentially generate tsunami wave from submarine landslides that will impact the coastline at Sulawesi and Kalimantan [7].

The volume of the slide material and other parameters such as angle of the slide, water depth, density of the slide material, the speed of the material moves, and duration of the slide are the factors that influence tsunami generation from submarine landslides [8]. Previous study regarding this the simulation of tsunami landslide is shown at Table 1 with different study areas, methods, and the landslide volume.

| Author | Study Area | Numerical Model | Landslide Volume |
|--------|------------|-----------------|------------------|
| Schambach et. al., (2020) [9] | Palu (28th September 2018) | NHWAVE and FUNWAVE | 0.3 km³ – 6.6 km³ |
| Heinrich et. al., (2001) [10] | Papua New Guinea (17 July 1998) | The Navier–Stokes (NS) model and Shallow Water model (SW) | 4 km³ |
| K Pakoksung et al. (2019) [11] | Palu (28th September 2018) | TUNAMI N2 | 0.1 km³ to 0.59 km³ |
| Brune et. al, (2010a) [12] | Padang | TUNAMI N2 | 0.7 km³, 0.5 km³, and 0.1 km³ |
| Kongko and Karima (2020) [13] | Sunda Strait (22nd December 2018) | TUNAMI N3 | 0.75 km³ |
| Gumbira et al. (2021) [14] | Makassar Strait | NHWAVE and FUNWAVE | 5 km³, 8 km³, 70 km³, 200 km³ |

One of the deadliest tsunamis occurred at Papua New Guinea by 1998 and caused 2200 fatalities [10]. The Papua New Guinea tsunami triggered by landslide or mass movement [15] and [16]. The simulation model applied for this event using Navier-Stokes and Shallow-Water models. The scenario that suited for inundation height with the volume of 4 km³ situated at water depth 550 m. The simulation showed that profile of water surface influenced by the constitutive law of the landslide [10]. The models used for tsunami simulation at Palu, 28th September 2018 were both nonlinear using NHWAVE (3D non-hydrostatic model) and FUNWAVE (2D Boussinesq model), with tsunami landslide source simulated as granular material [9]. Bathymetry and topography conditions in Majene waters have quite steep slopes, so there is a high risk of landslides. This study concluded that it is necessary to explain the elevated tsunami simulation with additional tsunami mechanism (submarine landslide). According to [11], there are two geologic mechanism that affect seafloor surface which are seismic-tectonic activity and sedimentary instability processes resulting in landslide.

In the same year in Indonesia, there was a devastating tsunami located at Sunda Strait caused by landslide tsunami near Anak Krakatau Mountain [13]. According to [8], tsunami generation from submarine landslides depends on the volume of the slide material. One simulation using non-linear model had been conducted and the landslide scenario that had the best fit with marioogram data is 0.175 km³ of volume [13]. In addition, tsunami modeling due to the landslide of Anak Krakatau has also been
carried out using a different manning number scenario with MIKE 21 software [17]. In addition, Padang is one of region that has 70 km of landslide potential according to bathymetry surveys [18]. Tsunami simulation already conducted for this area using scenario of 0.5-25 km$^3$ of volume by [18]. The maximum run-up for this scenario is about 3 m [18]. Submarine landslide tsunami has also been modelled by [14] in Makassar Strait. The research was about the potential of submarine landslide tsunami and its impact to Kalimantan Island by using NHWAVE and FUNWAVE model.

On 14th January 2021 there were two earthquake events hit Majene, West Sulawesi with magnitude of M 5.9 and followed by the second earthquake at 15th January 2021 at 01.28.17 (UTC+7) with a magnitude of M 6.2 [19]. The latter event caused 84 fatalities, 189 people had fatal injured in Mamuju and 64 people in Majene, and 15,000 of people evacuated [20] and [1]. According to [19], this earthquake occurred on two different fault planes which were Somba and Mamuju. This devastating earthquake can potentially affect 59,543 people in Majene Regency, 62,007 of Mamasa Regency people, 144,377 people in Mamuju Regency, and 219,105 people of Polewali Mandar Regency [1]. Based on the results of the 1969 Majene tsunami reconstruction conducted by [21] the tsunami that occurred was the result of local coastal landslides based on the calculation of the ratio of the tsunami run-up height to the lateral distribution distance ($l_2$). According to earthquake event at Majene on 15th January 2021, it is observed that there is a potential submarine landslide in the area. In this study, tsunami landslide will be simulated to address the potential tsunami wave height and tsunami arrival time at Majene, West Sulawesi by using the combination of two model; NHWAVE as a generating source and FUNWAVE for the tsunami propagation.

2. Data and Method

To generate and propagate the tsunamis, we use a combination of two wave models, the 3D non-hydrostatic model NHWAVE and the 2D Boussinesq model FUNWAVE-TVD. Both models are nonlinear and address the physics of wave frequency dispersion critical in modeling tsunamis from landslides.

The domain bathymetry was obtained from National Bathymetry [22] with spacing grid 300 m x 300 m (Figure 1 and 2). The input data used in the modeling of the submarine landslide tsunami is the volume value of the submarine erosion, where the value includes the thickness, the width, and the length of the landslide (Table 3). The slide angle and bottom slope are also defined in this modeling with three experimental volumes, namely 1 km$^3$, 0.8 km$^3$, and 0.5 km$^3$ (Table 3) with the coordinate in Table 2. Those numbers picked according to the reference of Press Release from BMKG in 2021 as a worst case [23]. The 3D non-hydrostatic NHWAVE model is running to be able to generate tsunami sources based on the data that has been inputted. Based on the source of the tsunami, followed by modeling to obtain the propagation of tsunami waves using the FUNWAVE-TVD the 2D Boussinesq model. The position value of the tsunami source from the NHWAVE model and the time step are used as input for modeling the propagation of tsunami waves using FUNWAVE – TVD. This tsunami simulation conducted for an hour for NHWAVE and 3 hours for FUNWAVE with timesteps of 60 seconds for both simulations.

| Table 2. Earthquake source and landslide area coordinate. |
|----------------------------------------------------------|
| Longitude (°E)                | Latitude (°S)               |
| Earthquake source            | 118.894                     | 2.98                         |
| Landslide area               | 118.8525 – 118.8451         | 3.05443 - 3.05155            |
Figure 1. Landslide area and earthquake source (star symbol) at West Sulawesi, 15th January 2021 [23]

Figure 2. The domain of NHAVE model (red box) dan FUNWAVE-TVD model (black box)

| Tabel 3. Input data scenario for submarine landslide tsunami modeling using NHAVE and FUNWAVE -TVD. |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Scenatio 1 (Vol = 0.5 km$^3$) | Scenatio 2 (Vol = 0.8 km$^3$) | Scenatio 3 (Vol = 1 km$^3$) |
| Length | 2000 m | 2000 m | 2000 m |
| Width | 500 m | 500 m | 500 m |
| Thickness | 500 m | 800 m | 1000 m |
| Slope angle | 15° | 15° | 15° |
| Slide angle | 200° | 270° | 200° |
Figure 3. Bathymetry of NHWAVE model domain and its observation points (red dots).

The output from this submarine landslide tsunami modeling is the tsunami wave height value at each observation point that located at the onshore (Figure 3). Observation points 1 to 40 are considered as tsunami-affected areas and are defined in Table 4.

Table 4. The locations of observation points

| No | Longitude (°E) | Latitude (°S) | Regency | District | Sub-district |
|----|----------------|---------------|---------|----------|--------------|
| 1  | 118.998        | -2.553        | Mamuju  | Kalukku  | Sinyonyoi    |
| 2  | 118.968        | -2.587        | Mamuju  | Kalukku  | Bebanga      |
| 3  | 118.939        | -2.622        | Mamuju  | Mamuju   | Tadui        |
| 4  | 118.909        | -2.655        | Mamuju  | Mamuju   | Karampuang   |
| 5  | 118.870        | -2.672        | Mamuju  | Mamuju   | Simboro      |
| 6  | 118.844        | -2.635        | Mamuju  | Mamuju   | Sumare       |
| 7  | 118.818        | -2.607        | Mamuju  | Mamuju   | Sumare       |
| 8  | 118.800        | -2.648        | Mamuju  | Mamuju   | Sumare       |
| 9  | 118.781        | -2.689        | Mamuju  | Mamuju   | Sumare       |
| 10 | 118.762        | -2.730        | Mamuju  | Tapalang  | Labuang Rano |
| 11 | 118.749        | -2.773        | Mamuju  | Tapalang  | Lebani       |
| 12 | 118.747        | -2.818        | Mamuju  | Tapalang  | Dungkait     |
| 13 | 118.747        | -2.863        | Mamuju  | Tapalang  | Dungkait     |
| 14 | 118.777        | -2.891        | Mamuju  | Tapalang  | Dungkait     |
| 15 | 118.821        | -2.883        | Mamuju  | Tapalang  | Orobatu      |
| 16 | 118.855        | -2.901        | Mamuju  | Tapalang  | Galung       |
| 17 | 118.852        | -2.942        | Majene  | Majene    | Mekkatta     |
| 18 | 118.834        | -2.983        | Majene  | Majene    | Lombang      |
| 19 | 118.832        | -3.027        | Majene  | Majene    | Malanda      |
| 20 | 118.808        | -3.052        | Majene  | Majene    | Sambabo      |
| 21 | 118.764        | -3.061        | Majene  | Sedana    | Tubo         |
| 22 | 118.756        | -3.104        | Majene  | Sedana    | Onang        |
| 23 | 118.770        | -3.144        | Majene  | Sedana    | Onang        |
| 24 | 118.799        | -3.176        | Majene  | Sedana    | Onang        |
| 25 | 118.812        | -3.219        | Majene  | Sedana    | Ulibang      |
| 26 | 118.814        | -3.264        | Majene  | Sedana    | Tammerodo    |
| 27 | 118.816        | -3.310        | Majene  | Sedana    | Sedana       |
| 28 | 118.821        | -3.354        | Majene  | Pamboang  | Puttada      |
| 29 | 118.829        | -3.399        | Majene  | Pamboang  | Mosso        |
| 30 | 118.843        | -3.441        | Majene  | Pamboang  | Sirindu      |
| 31 | 118.862        | -3.482        | Majene  | Pamboang  | Lalampanuua  |
3. Results and Discussion

3.1 The NHWAVE Simulation

The NHWAVE simulation results show the initial elevation of waves caused by submarine landslide. It is observed that Deking district hit by the first tsunami wave for all scenarios at -2.4 m, -0.5 m, and -2.5 m (Figure 4, 5, and 6). The wave heights at Deking show similar pattern in every landslide volume (Figure 4, 5, and 6). The initial tsunami wave from the NHWAVE modeling had a height of 0.33 m at Mamuju based on a volume of 1 km$^3$ (Figure 5). The slope direction defines the direction of the fall of submarine landslide.

In this case, all the scenarios had the same slope angle, which is 15°. It is seen from the figures (4, 5, and 6) that the peaks of elevation are coloured red. The difference in landslide volume produced the difference in the width of areas affected by the initial tsunami wave. The higher volume, the wider initial tsunami wave areas will be influenced. It is shown in Figure 5 that has larger affected area than Figure 3 or 4.

![Figure 4](image_url)

**Figure 4.** The NHWAVE Simulation result with volume of 0.5 km$^3$. The map of tsunami wave generation at West Sulawesi (left) and the timeseries-elevation of tsunami wave generation at Mamuju, Deking, Somba, Majene, and Polewali (right).
Figure 5. The NHWAVE Simulation result with volume of 0.8 km$^3$. The map of tsunami wave generation at West Sulawesi (left) and the timeseries-elevation of tsunami wave generation at Mamuju, Deking, Somba, Majene, and Polewali (right).

Figure 6. NHWAVE Simulation result with volume of 1 km$^3$. The map of tsunami wave generation at West Sulawesi (left) and the timeseries-elevation of tsunami wave generation at Mamuju, Deking, Somba, Majene, and Polewali (right).

Based on Figure 4, the maximum distance of the 0.5 km$^3$ volume is 18 km. Meanwhile, the maximum distance of 0.8 km$^3$ and 1 km$^3$ are 22,5 and 25,5 km (Figure 5 and 6). The maximum elevation of initial waves illustrated in Figure 7. The highest elevation is about 1.3 meter located at Kecamatan Majene. It is seen that the higher elevation occurred at observation points at 14-24, for three scenarios, which situated at Kecamatan Tapalang, Majene, and Sedana. Based on NHWAVE modelling, it is estimated that the tsunami arrives at the coast within 5 - 20 minutes.
3.2 The FUNWAVE-TVD Simulation

The second simulation conducted using FUNWAVE. The purpose of this model is to analyze the tsunami wave propagation using the tsunami source that obtained previously from NHWAVE simulation. The source of the tsunami wave is the final result of the NHWAVE model with a simulation time of 1 hour and then used as input data (initial elevation) of the FUNWAVE-TVD model. The scenario used for this simulation is the largest volume which is 1 km$^3$. The propagation of tsunami is directed to the south and the north, however, the highest elevation propagates to the south (red colour) (Figure 8) and affected West Sulawesi. Some part of Kalimantan like Bontang and Delta Mahakam also influenced by the tsunami wave. Figure 7 shows the results of tsunami wave propagation as a result of FUNWAVE simulation. Based on the modeling results, the tsunami waves propagate to the southwest. In the 180th minute, the tsunami wave was still propagating towards the north of Sulawesi Island to the east of Kalimantan Island.

Figure 7. The Maximum tsunami source elevation at observation points from NHWAVE Simulation

Figure 8. Tsunami propagation after 90 minutes, 135 minutes, and 180 minutes with the volume of 1 km$^3$.

4. Conclusion

According to earthquake event at Majene on 15th January 2021, it is observed that there is a potential submarine landslide in the area. Three different scenarios with three different volumes (1 km$^3$, 0.8 km$^3$, 0.5 km$^3$) were simulated using NHWAVE and FUNWAVE-TVD models.
and 0.5 km$^3$) were conducted as the input for tsunami simulation. The first simulation used was NHWAVE simulation to generate the initial wave from the landslide source. It is observed that different volume shows different affected areas. The maximum distance of the 0.5 km$^3$ volume is 18 km. Meanwhile, the maximum distance of 0.8 km$^3$ and 1 km$^3$ are 22.5 km and 25.5 km, respectively. Deking District and Mamuju are locations that hit by the wave. The highest tsunami source elevation for 1 km$^3$ landslide-volume is 1.2 m, while for 0.8 km$^3$ and 0.5 km$^3$ landslide volume is 1 m and 0.4 m, respectively, located at Tapalang Sub-district, Majene and it was used as an input (initial elevation) for FUNWAVE-TVD model. Based on NHWAVE modelling, it is estimated that the tsunami arrives at the coast within 5 - 20 minutes. The FUNWAVE simulation result is the tsunami wave propagation for 180 minutes later. In the 180th minute, the tsunami wave was still propagating towards the north of Sulawesi Island to the east of Kalimantan Island.

5. Author Contributions
In this study all authors are the main contributors. HK, SK preprocessing data, setup and modelling, analysis of modelling results. GG and RA make scenarios and analysis of modelling results. All authors reviewed this manuscript.

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