Run-up Height and Flow Depth Simulation of the 2006 South Java Tsunami Using COMCOT on Widarapayung Beach

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Abstract. The destructive force of the tsunami could induce a considerable amount of casualties, infrastructures, and properties. One of the large tsunamis in Indonesia is 2006 South of Java Tsunami. There were 664 fatalities, 498 injured, 55 million dollars in losses, and 1623 homes damaged. Simulations of flow depth and run-up of the 2006 tsunami on Widarapayung Beach have never been conducted. Although they can be used as a basis for determining tsunami hazard zones. The method that might be used for tsunami impact analysis is tsunami waves modeling by considering the focal mechanism. The aims of this research are to determine the run-up height and flow depth of the 2006 tsunami on Widarapayung Beach. The calculations of modeling were performed using COMCOT numerical model. It operates calculations by solving shallow water equations in both linear and non-linear equations. Using this model, the generation and propagation of tsunami in a multi-grid system could be simulated. The result of the simulations on three different models depicts that the maximum run-up height on Widarapayung Beach is 3 to 3.8 m. The flow depth result from the three different models also suggests vulnerable areas up to 1 km from the shoreline.

1. Introduction
The destructive force of tsunami can cause a considerable amount of fatality and infrastructure damage. One of such tsunami is the 2006 South Java Tsunami (Fig. 1). This event occurred at 225 km from Pangandaran Beach (9.222°S, 107.320°E) with 7.7 on the Richter scale [1]. Based on a survey carried out by [2], this tsunami resulted in 664 fatalities. While based on the [3] survey in South Java 802 fatalities, 498 injuries, 55 million dollars in losses, and 1623 homes destroyed. On Pangandaran Beach, the intensity of the tsunami in the Papadopoulos and Imamura scale reached values IX and X (destructive to very destructive) [4]. The tsunami is a series of rapid long waves caused by large disturbance of a water body. To cause large scale disturbance, the event needs to release a large amount of energy in a short period of time. A tsunami usually triggered by fault displacement deep inside the convergence plate boundary. Most of the time it was caused by an earthquake but a big enough landslide that releases large amounts of energy could also trigger tsunami [5]. The July 17, 2006 tsunami in South Java was triggered by a small-scale earthquakes[6]. The local resident at the time barely felt the tremor of the earthquake [7]. In 2006, [8] conducted research using a long-period body and Rayleigh waves. The research focused on the mechanism of deformation fault and obtained an estimation of 1.0-1.5 km/s rupture velocity. With the low velocity and a short duration of 185 s, this earthquake is considered to have a slow breaking speed. These are in accordance with the characteristics of a tsunami earthquake [8].
As disaster countermeasures, numerical modeling can be used to obtain a mapping of inundation areas. The inundation map then can be used to identify areas prone to tsunami flooding and to take preventative measures [9]. The propagation and run-up data obtained from modeling are verified by observations in the field so that we can get a reliable map of vulnerable areas [10]. Widarapayung Beach is a beach tourist attraction located in Widarapayung Village, Binangun District, Cilacap Regency, Central Java, Indonesia. The location is about 35 km to the east of Cilacap. This beach was hit by the 2006 tsunami in South Java. This event occurred on July 17, 2006. It caused many fatalities and infrastructure damages. Based on a field survey by [11] run-up height on Widarapayung Beach is around 4 meters. Meanwhile, according to [12], the height of the tsunami run-up reached 4.26 meters.

Cornell Multi-grid Coupled Tsunami Model (COMCOT) is used to study the entire tsunami process, from generation, propagation to inundation. Using a modified leap-frog finite difference numerical method, it can solve shallow water equations as the basis of the simulation [5]. Although the 2006 Java tsunami has been studied by many researchers, there is no research on the tsunami hazard zones around the southern Cilacap coastal area. Using tsunami modeling, we simulate the 2006 tsunami to understand the physical impact of the tsunami and delineate the area vulnerable to future tsunami. The coast between Cilacap city and Kebumen is known to be a tourism destination [2]. Besides many tourists, the coast is also occupied as residential areas [10]. Therefore, this research is important to determine the tsunami inundation in the southern of Cilacap. We believe that Widarapayung Beach could represent the tsunami risk in the southern of Cilacap.

2. Method
Tsunami modeling is used to simulate the whole of a tsunami process beginning from generation, propagation, and inundation at the coast using sets of mathematical formulas. With the simulated result, we can understand physical characteristics like flow depths, wave speeds, amplitude, and inundation range. There are two types of tsunami modeling: numerical models and empirical models [12]. In this research, we use a numerical model which is a simulation of the mathematical models using computers. Numerical tsunami modeling involves three stages: source modeling, propagation modeling, and inundation modeling. Source modeling is the simulation on the generation of the tsunami, either by an earthquake, a submarine landslide, a volcanic eruption, or a bolide impact. Propagation modeling is the simulation of the movement and dispersal of the waves from the initial deformation area. Inundation modeling is the simulation of the water flow over the shoreline [13]. One of the models that are currently used by researchers for tsunami modeling is COMCOT.

COMCOT tsunami source model is based on [5] formula. The initial seafloor deformation for the propagation is calculated with the [5] formula. This formula assumes the earthquake represents a finite dislocation within an elastic body. Tsunami model COMCOT implements shallow water equations, either in Spherical or Cartesian Coordinates to simulate the propagation and run-up of Tsunami. For
this study, we used Spherical Coordinates both the linear and nonlinear equations. Linear shallow water equations in spherical coordinates used in COMCOT is as below:

\[
\frac{\partial \eta}{\partial t} + \frac{1}{R \cos \varphi} \left( \frac{\partial P}{\partial \psi} (\cos \varphi Q) \right) = - \frac{\partial h}{\partial t}
\]

\[
\frac{\partial P}{\partial t} + \frac{g h}{R \cos \varphi \cos \psi} \frac{\partial \eta}{\partial \psi} - fQ = 0
\]

\[
\frac{\partial P}{\partial t} + \frac{g h \partial \eta}{\partial \varphi} + fP = 0
\]

Water surface elevation is denoted with \( \eta \). The volume flux components in x and y directions are denoted with \( P \) and \( Q \) respectively. Latitude and longitude of the Earth are denoted with \( \varphi \) and \( \psi \). The radius of the earth is denoted with \( R \). Gravitational acceleration is denoted with \( g \). Water depth is denoted with \( h \). Due to the rotation of the Earth Coriolis force coefficient is used and represented with \( f \) and lastly rotation of the Earth is denoted with \( \Omega \) [5].

\[
f = \Omega \sin \varphi
\]

As tsunami wave propagates over the continental shelf and into the coastal area the wave-length of the incident tsunami becomes shorter and the amplitude becomes larger therefore linear shallow water equations become invalid. In coastal areas as waves become nearer to shore nonlinear convective inertia force and bottom frictions, terms are getting more important while Coriolis force and the frequency dispersion become less important. Thus the nonlinear shallow water equations including bottom frictions effect are adequate [14]. The non-linear shallow water equations used in COMCOT for spherical coordinates are as below:

\[
\frac{\partial \eta}{\partial t} + \frac{1}{R \cos \varphi} \left( \frac{\partial P}{\partial \psi} (\cos \varphi Q) \right) = - \frac{\partial h}{\partial t}
\]

\[
\frac{\partial P}{\partial t} \frac{1}{R \cos \varphi} \frac{\partial}{\partial \psi} \left( \frac{P^2}{H} \right) \frac{1}{R \varphi} \frac{\partial \left( \frac{PQ}{H} \right)}{\partial \psi} + \frac{gH}{R \cos \varphi} \frac{\partial \eta}{\partial \psi} - fQ + F_x = 0
\]

\[
\frac{\partial Q}{\partial t} \frac{1}{R \cos \varphi} \frac{\partial}{\partial \psi} \left( \frac{Q^2}{H} \right) \frac{1}{R \varphi} \frac{\partial \left( \frac{PQ}{H} \right)}{\partial \psi} + \frac{gH}{R \varphi} \frac{\partial \eta}{\partial \varphi} + fQ + F_x = 0
\]

Water depth is denoted with \( H \). Bottom friction in x and y are denoted with \( F_x \) and \( F_y \) respectively. \( F_x \) and \( F_y \) are also evaluated using Manning’s formula. Manning’s roughness coefficient is denoted with \( n \).

\[
F_x = \frac{g n^2 P (P^2 + Q^2)^{1/2}}{H^2}
\]

\[
F_y = \frac{g n^2 Q (P^2 + Q^2)^{1/2}}{H^2}
\]

The parameters used for the fault model are modified data compiled from [14] and [15]. The epicenter location we used for the fault model is from field observation by [16]. For Model 1 we used data extracted from [17]. In their research, they used GSN broadband waveforms to obtain the slip history using a finite fault inverse algorithm. For Model 2, we used data from research by [18]. Using inversion of tsunami waveforms, they concluded the tsunami source was 200 km long with a slip of about 2.5 meters. For Model 3, we used data from research by [19]. The slip dislocation varies
between 8-15 meters. In this model, we used the average value of 12 meters instead. [18] found that the slip distribution at the source is distributed unevenly with five to six sharp differences near the epicenter. However, in this research, we only used a single uniform fault in our source (Table 1).

| Table 1. Compiled fault parameters |
|-----------------------------------|
| Fault Parameter                  | Model 1 [17] | Model 2 [18] | Model 3 [19] |
| Slip Angle (degree)              | 93           | 95           | 95           |
| Strike (degree)                  | 297          | 289          | 289          |
| Dip (degree)                     | 6            | 10           | 10           |
| Depth (km)                       | 10           | 10           | 12           |
| Dislocation (meter)              | 5            | 2.5          | 12           |
| Fault Width (km)                 | 40           | 40           | 40           |
| Fault Length (km)                | 200          | 200          | 200          |
| Epicenter (long)                 | 107.310997   | 107.310997   | 107.310997   |
| Epicenter (lat)                  | -9.22999954  | -9.22999954  | -9.22999954  |

3. Bathymetry and topography

The data read by COMCOT need to be written in 3 columns for longitude, latitude, and water depth. On reading bathymetry and land topography data, COMCOT has a particular way of reading data from the file format. Water depth in ETOPO file format the data will be read based on the sign of the number, negative sign means the data is below the water surface and positive sign means the data is above water surface [15]. Thus COMCOT can read data directly from the ETOPO file format. Other than ETOPO file format, COMCOT can also read data from the XYZ file format or its old propriety file format, just with the slight change of sign. In ETOPO data. The bathymetry data we used, however, is ETOPO1 data from [14]. ETOPO1 is a 1 arc-minute global relief model of Earth’s surface that integrates land topography and ocean bathymetry. In Figure 2 the deep blue color shows the deeper water depth and green color show the shallower water depth. The negative sign illustrates under mean sea level. On the other hand, a positive sign shows above mean sea level.

![Figure 2](image-url)

**Figure 2.** the bathymetry data and model domain. A red box displays the parent layer grid area. A pink box depicts the sub layer 1 grid area. A blue box shows the sub layer 2 grid area. A green box illustrates the fault dimension and direction.
4. Numerical domain and setup

In this research, we used a nested grid form with three different grid levels and grid resolution. The first grid or layer encompass big regions below the south coast of Java with 106.208504 to 109.433746 longitude and -7.55985355 to -10.0633001 latitude. This layer uses linear shallow water equations with a grid dimension of 707x549 with a grid size of 0.27 arch minutes and a step size of 0.1366. The second encompasses the coast of Pangandaran to coast of Ayah with 108.381889 to 109.393776 longitude and -7.59982634 to -8.39243221 latitude. This layer uses non-linear shallow water equations with a grid size ratio of 2 to the parent layer. The third layer encompasses the area around Widarapayung Beach with 109.006989 to 109.364838 longitude and -7.62647533 to -7.90666676 latitude. In this layer, we use non-linear equations and enabled bottom friction with constant roughness of 0.013.

We compile run-up height data from several sources (Fig.3). From these data, we compared the simulated results and the observed data. As a comparison between simulated wave height and observed wave height, we choose four locations on the southern coasts of Java. The observed run-up height data and their respective sources are presented in Table 2.

![Figure 3. Bathymetry data and studied run-up location.](image)

| No | Locations   | Coordinates | Run-up Height (m) |
|----|-------------|-------------|-------------------|
|    |             | Longitude   | Latitude          | [2] | [11] | [17] |
| 1  | Ayah        | -7.72356    | 109.3949          |     | 6.7  | 1.9  |
| 2  | Widarapayung| -7.69597    | 109.2643          | 2-5 | 5    | 4.26 |
| 3  | Pangandaran | -7.6833     | 108.65            | 3-5 | 7.8  | 5    |
| 4  | Permisan    | -7.74184    | 108.8749          | 20  | 5-8  | 10-20|

5. Result and discussion

Based on the result of the simulation we compare the observed run-height on four locations on the southern coasts of Java and the maximum height from the models. The maximum height resulted from the simulation on those locations are presented in Table 3.

![Table 2. Compiled observed run-up height.](image)
Table 3. Compiled simulated run-up height.

| No | Locations    | Coordinates          | Simulated Maximum Run-up Height (m) |
|----|--------------|-----------------------|------------------------------------|
|    |              | Longitude            | Latitude  | [17] | [18] | [19] |
| 1  | Ayah         | -7.72356             | 109.3949 | 1.3 - 2 | 0.6 - 1 | 2.7 - 3 |
| 2  | Widarapayung | -7.69597             | 109.2643 | 2 - 2.4 | 1 - 1.5 | 3.5 - 3.8 |
| 3  | Pangandaran  | -7.6833              | 108.65   | 1 - 1.5 | 1.2 - 1.6 | 3 - 3.5 |
| 4  | Permisan     | -7.74184             | 108.8749 | 4.3 - 5 | 1.5 - 2 | 7.5 - 8 |

5.1. Model 1
Figures 4, 5, 6 show the tsunami propagation for the three models every 900s from 0 to 5400s with Model 1. With this model, using parameters from [17], tsunami waves first reach land at 1699s on Parang Kakapa Beach with a wave height of 7 meters. The Tsunami then hit Permisan at 2799s, Pangandaran at 3199, Ayah at 3259, and Widarapayung at 3600. The maximum run-height on Ayah is 1.3 to 2 m, 2 to 2.4 m on Widarapayung, 1 to 1.5 m on Pangandaran, and 4.3 to 5 m on Permisan. Figure x shows the maximum run-height on sub-grid 1. Compared to the observed run-up height, maximum run-up height from Model 1 fit with the data from [2] the most.

Figure 4. Tsunami propagations with Model 1 on parent layer grid every 15 minutes for 90 minutes

Figure 5. Tsunami propagations with Model 1 on sub layer 1 grid every 15 minutes for 90 minutes

Figure 6. Tsunami propagations with Model 1 on sub layer 2 grid every 15 minutes for 90 minutes
5.2. Model 2
Figures 7, 8, 9 show the tsunami propagation for the three models every 900s from 0 to 5400s with Model 2. With this model, using parameters from research by [18], tsunami waves first reach land at 1699s on Parang Kakapa Beach with a wave height of 3 meters. The Tsunami then hit Permisan at 2799s, Pangandaran at 3199, Ayah at 3259, and Widarapayung at 3600. The maximum run-height on Ayah is 0.6 to 1 m, 1 to 1.5 m on Widarapayung, 1.2 to 1.6 m on Pangandaran, and 1.5 to 2 m on Permisan. Model 2 compared to the other 3 models generated the smallest tsunami waves and run-up height on the 4 study locations. Compared to the observed run-up height, the maximum run-up height from Model 2 is much smaller than any of the observed data. This may be caused by the small slip dislocation of only 2.5 m.

![Figure 7](image1.png)

**Figure 7.** Tsunami propagations with Model 2 on parent layer grid every 15 minutes for 90 minutes

![Figure 8](image2.png)

**Figure 8.** Tsunami propagations with Model 1 on sub layer 1 grid every 15 minutes for 90 minutes

![Figure 9](image3.png)

**Figure 9.** Tsunami propagations with Model 1 on sub layer 2 grid every 15 minutes for 90 minutes

5.3. Model 3
Figures 10, 11, and 12 show the tsunami propagation for the three models every 900s from 0 to 5400s with Model 1. With this model, using parameters from research by [19], tsunami waves first reach land at 1699s on Parang Kakapa Beach with a wave height of 12 meters. The Tsunami hit Permisan at 2799s, Pangandaran at 3199, Ayah at 3259, and Widarapayung at 3600. The maximum run-height on Ayah is 2.7 to 3 m, 3 to 3.8 m on Widarapayung, 3 to 3.5 m on Pangandaran, and 7.5 to 8 m on Permisan. Model 3 compared to the other 3 models generated the biggest tsunami waves and run-up height on the 4 study locations. Compared to the observed run-height, maximum run-up height from Model 3 fit closer with the data from USGS the most.
Figure 10. Tsunami propagations with Model 2 on parent layer grid every 15 minutes for 90 minutes

Figure 11. Tsunami propagations with Model 1 on sub layer 1 grid every 15 minutes for 90 minutes

Figure 12. Tsunami propagations with Model 3 on sub layer 2 grid every 15 minutes for 90 minutes

5.4. Flow depth at Widarapayung
In this study, we also calculated the flow depth at Widarapayung Beach. With this, we intend to find out how far water inundated inland with all three models. This information will help in determining area vulnerable areas for future tsunami hazard mitigation. For all three models, we use non-linear shallow equations and take account of the bottom friction. A new grid was made around Widarapayung Beach with a grid size ratio of 3 to its parent layer. We also overlay satellite images taken in 2020 of Widarapayung Beach into the grid. Based on the simulated flow depth, in model 1 the tsunami wave inundated about 600-750 meters inland. In model 2 the tsunami wave inundated about 300-450 meters inland. While in model 3 the tsunami waves inundated about 750 to 1000 meter inland. Out of all three models, 2 inundated the shortest, and model 3 inundated the furthest. Figure 13 shows the flow depth of all three models and their wave height. However, data from [3] illustrate only 76-meter horizontal inundation at Widarapayung.
Figure 13. Simulated flow depth, black line refer to the coastline based on the ETOPO1 bathymetry data a). Model 1 b). Model 2 c). Model 3

6. Conclusion
Based on the result of the simulation (Fig. 14 and 15), model 1 and 2 generated too small tsunami waves and run-up height at the study location. This might be because of an insufficient amount of slip and focal depth. We concluded model 3 using the fault parameter compiled from research by [19] fit the observed run-up height better. Based on the simulation, the tsunami hit Permisan at 2799s, Pangandaran at 3199, Ayah at 3259, and Widarapayung at 3600. The maximum run-height on Ayah is 2.7 to 3 m, 3 to 3.8 m on Widarapayung, 3 to 3.5 m on Pangandaran, and 7.5 to 8 m on Permisan. The huge difference between observed run-up height and simulated run-up height at Permisan presumably because the data collected are from the inundated wave that hit the cliffsides around Permisan instead of the beach. Between the three models, it can be inferred that the slip amount and the focal depth had a big role in generating the maximum tsunami height. The horizontal inundation based on Model 3 is 750 to 1000 at Widarapayung.

Figure 14. Maximum simulated wave height of model 1.
Figure 15. Maximum simulated wave height of model 2 (a) and model 3 (b)

7. References

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