Study of Characteristics and the Coverage of Tsunami Wave Using 2D Numerical Modeling in the South Coast of Bali, Indonesia

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Abstract

The location of Indonesia, which is on the three main tectonic plate boundaries, makes Indonesia prone to disasters, including the tsunami. One of the vulnerable areas to tsunami disaster is the southern coast of Bali Province because it is close to the Bali Megathrust subduction zone. The Sumbawa earthquake on August 19, 1977, was an event that occurred at the subduction zone with a strength of 8.3 Mw then caused a tsunami. Studies of wave characteristics and tsunami coverage areas in Bali are rare. This study was aimed to examine the characteristics of waves and tsunami’s coverage areas in the south of Bali Province (Denpasar and Badung). We used 2D numerical modeling for the simulation of tsunami waves that built using COMCOT version 1.7. The travel time from the tsunami’s formed to the coast was ranged between 30–39 minutes. The maximum wave height is 16.73 meters at the Uluwatu observation point, because it is close to the tsunami’s epicenter. Meanwhile, the wave heights at the observation points in Denpasar City and the northern of Badung Regency were ranged from 4.84 to 6.9 meters because the waves can be muted at the southern area of Bali Island. The area of tsunami coverage in Denpasar City reached 65.86 km² and in Badung Regency is 61.17 km².

Keywords: Tsunami, Inundation Area, Numerical Modeling, COMCOT, Bali Province
INTRODUCTION

Tsunami is the vertical movement of seawater bodies caused by geological processes [4]. The dominant geological process in producing tsunami waves is an earthquake centered on the ocean floor [5], landslides on the sea floor [25], and volcanic activity on the sea floor [4]. Tsunami can occur at subduction zones [9] and if they move towards shallow waters, they will have large and destructive energy [17].

Tsunami has been studied widely in various countries, such as in the Makran subduction zone [14], in Tohoku, Japan [21], and Marmara Sea, Turkey [7]. There were several studies about tsunami in Indonesia [8; 2; 12], but those only covered areas that were significantly affected by the tsunami. Study on the areas that are not prone to tsunamis, but have great potential to occur, is very important, and one these areas is in Bali.

Bali Island area has the potential to be affected by the tsunami because it is close to the subduction zone, the Bali Megathrust [10]. Bali Megathrust extends from the south of Bali Island to the south of Sumba Island, East Nusa Tenggara [18]. The Sumbawa earthquake on August 19, 1977, was a disaster that occurred at the subduction zone with a strength of 8.3 Mw then caused a tsunami [13].

Until now, Bali has suffered a smaller tsunami impact from other regions in Indonesia, but the worst cases can occur in the future. Records from the USGS (United States Geological Survey) found that there were at least 47 earthquakes with strength more than 5 Mw from 1973 to 2018 in the south of Bali [22]. Therefore, the study about the impact of the tsunami in Denpasar City and Badung Regency is really important, because these areas are the center of people's lives on Bali Island, considering that study about tsunamis in these areas are still rare.

The aimed of this study was to examine the characteristics of tsunami about the travel time of the waves, the height of the waves on the coast and observe the affected area by the tsunami in the southern Bali Province (Denpasar and Badung). Simulations carried out using the data history of the Sumbawa tsunami in 1977 with the epicenter placed in the southern subduction zone of the island of Bali. Tsunami modeling was built using COMCOT version 1.7 [23] which was carried out in various studies [1; 16; 19].

MATERIALS AND METHODS

Study Area

The location of this study is in the southern of Bali Island, from coastal areas until the subduction zone of Bali Megathrust in the Indian Ocean. This study used 2 layers to determine the extent of the study area, with the first layer coordinates is 110.5ºE – 120.8ºE and 5.95ºS – 13.868ºS, while the second coordinates are 114.4ºE – 115.5ºE and 8.59ºS – 8.89ºS (Figure 1). Layer 1 shows the entire study area, while layer 2 shows the southern Bali Province, Denpasar City, and Badung Regency.
In this study, the wave height measurement point was placed at 5 locations. The determination of wave measurement points was adjusted to the population density and tourism areas. The wave measurement point placed at 10 meters depth for better results [20].

Bathymetry and Topography

Bathymetry and topography data used the ASCII (American Standard Code for Information Interchange) format. The bathymetry data that used in this study was the integration data published by BODC (British Oceanographic Data Center) with 15 arcs second scale on 2019 and National Bathymetry Data published by BIG (Badan Informasi Geospasial) with 6 arcs second scale. The topography data is the gridding process of high point data and contour lines from the RBI map (Rupa Bumi Indonesia) with scale 1:25.000, published by BIG (Badan Informasi Geospasial) in 2012.

Tsunami Generator Parameters

The tsunami generation originates from tectonic earthquake or plate shift earthquake sources. The parameters used in this study are earthquake magnitude, epicenter depth, plate shift angle (Strike, Dip, Slip), dislocation, fault length, and width of the fault. The tsunami generator parameters were published by USGS (United State of Geological Survey) by taking the Sumbawa tsunami in 1977, while in calculating the value of the length of the fault, the width of the fault and plate dislocation using the equation developed by Wells and Coppersmith [26] as follows:

\[
\text{Log } L = -3.55 + 0.74 \times \text{Magnitude (Mw)} \tag{1}
\]
\[
\text{Log } W = -0,76 + 0,27 \times \text{Magnitude (Mw)} \\
\text{Log } D = -7,03 + 1,03 \times \text{Magnitude (Mw)}
\]

Where \( L \) is the length of the fault, \( W \) is the width of the fault, and \( D \) is the dislocation.

2D Numerical Modeling

In this study, 2D numerical modeling for tsunami wave simulation was built using Cornell Multi-grid Coupled Tsunami models. The basic equation used is Shallow Water Equations which is explained as follows:

Linear shallow water equation, used in calculating waves in deep waters [24].

\[
\frac{\partial \eta}{\partial t} + \left( \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right) = \frac{\partial h}{\partial t} \\
\frac{\partial P}{\partial t} + gh \frac{\partial \eta}{\partial x} - fQ = 0 \\
\frac{\partial Q}{\partial t} + gh \frac{\partial \eta}{\partial y} + fP = 0
\]

Non-linear shallow water equation, used in calculating waves entering shallow and inland waters [24].

\[
\frac{\partial \eta}{\partial t} + \left( \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right) = \frac{\partial h}{\partial t} \\
\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{H} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{H} \right) + gh \frac{\partial \eta}{\partial x} + F_x = 0 \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{PQ}{H} \right) + \frac{\partial}{\partial y} \left( \frac{Q^2}{H} \right) + gh \frac{\partial \eta}{\partial y} + F_y = 0
\]

Where \( \eta \) is the water level elevation (m), \( P \) and \( Q \) are the volume of the flux (x-direction and y-direction), \( H \) is the total depth (\( \eta + h \)), \( h \) is the depth of water, \( g \) is the gravitational acceleration, \( F_x \) and \( F_y \) are lower friction water (x-direction and y-direction), and \( f \) is the coriolis force coefficient.

Model Validation Method

The validation process was conducted to determine Cornell Multi-grid Coupled Tsunami model accuracy with scenario a tsunami in the southern Bali. The validation process of the model results using the historical simulation of the Sumbawa tsunami in 1977. The results of the tsunami wave height in the simulation will be compared with the records of the tsunami data published by BNPB (Badan Nasional Penanggulangan Bencana) in 2009.
Tsunami Wave Simulation

The simulation of the tsunami generator using historical data on the Sumbawa earthquake and tsunami on August 19, 1977, with the epicenter located in southern Bali on the Bali Megathrust subduction zone. The details of the tsunami generator parameters applied in this study are, magnitude = 8.3 Mw, depth = 33 km, strike = 64º, dip = 34º, slip = 113º, length of fault = 390 km, width of fault = 30 km, and dislocation = 33 m. The distance between the epicenter that caused the tsunami up to the southern Bali Island is 243 km with the epicenter coordinates at 115,088638ºE and 11,073634ºS. The results of this scenario obtained the characteristics of tsunami wave from the epicenter to the coast.

Tsunami Inundation Area Simulation

The data flow results from the calculation of equation 5 in the model scenario have been used to determine the range of a tsunami. Then, the overlaying process between flow-depth data and land use results is carried out. This process produces inundation characteristics due to the tsunami on land and the area affected by the tsunami.

RESULT AND DISCUSSION

Model Validation

Based on the results of model simulations in the case of the Sumbawa tsunami in 1977 (Figure 2), the maximum wave height was 8.69496 meters. These results compared with the actual disaster, based on the BNPB record [3], was found an error value 0.69496 meters. Based on these results, proved that the application of the Cornell Multi-grid Coupled Tsunami model in the case of a tsunami scenario in southern Bali is appropriate because it has minimum error value and close to the actual disaster.

![Figure 2. Graph of validation model](image-url)
Initial Tsunami Conditions

Based on the simulation modeling results, it was found that the initial conditions of tsunami occurred in southern Bali (Figure 3). These results indicated that at the initial condition, sea level rise up to 6.185 meters and fall to 4.455 meters. Sea level rise variation in the initial condition depends on the earthquake strength and epicenter depth [11].

![Initial sea surface elevation](image)

**Figure 3.** Initial sea surface elevation

Tsunami Arrival Time

In determining the arrival time of tsunami waves on the coast, this study took 5 observation points in Badung Regency and Denpasar City. These 5 points are used based on population density and tourism area. The simulation results for determining the wave arrival time can be seen in Figure 4.
The results at the Uluwatu observation point indicate that the arrival time of the tsunami wave was 30.5 minutes, starting with sea level decrease of 5.82 meters and a tsunami wave of 16.73 meters. At Nusa Dua observation point, the arrival time of the tsunami wave was 31 minutes, starting with a sea level drop of 5.73 meters and a tsunami wave of 13.93 meters. At Sanur observation point, the arrival time of a tsunami wave was 37 minutes, starting with a sea level drop of 5.8 meters and a tsunami wave of 6.9 meters. At Kuta observation point, the arrival time of a tsunami wave was 38 minutes, starting with sea level of 4.13 meters and a tsunami wave of 5.43 meters. And at Mengwi observation point, the arrival time of the tsunami wave was 39 minutes, starting with a sea level drop of 4.91 meters and a tsunami wave of 4.84 meters. The time of arrival of a tsunami wave was affected by the distance of the tsunami epicenter to the coast [6], while the height of the tsunami wave can be
affected by the magnitude of the tsunami epicenter, bathymetry, and topography [27]. The propagation of tsunami waves from the epicenter to the spatial land area in this study can be seen in Figure 5.
Figure 5. Spatial simulation of tsunami; (a) 0 minute, (b) 30 minutes, (c) 60 minutes, (d) 90 minutes, (e) 120 minutes, (f) 150 minutes
Figure 5 showed that, when the tsunami wave approaches the coast, the wave height will increase. This is confirmed by the results of the maximum tsunami height distribution pattern shown in Figure 6. The height of the tsunami wave when approaching the coast was affected by the shallow sea floor, then wave accumulation occurred, so that the waves height increase [27].

![Figure 6. Maximum tsunami wave heights distribution](image)

**Tsunami Inundation**

From the results of the modeling simulation (Figure 7), there were found 4 tsunami inundation classes on land, very high (12–15.5 meters), high (8–12 meters), medium (4–8 meters), and low (0–4 meters). The Denpasar City has the impact of the tsunami wave with the area of coverage 65.86 km$^2$. While the area impacted in Badung Regency was 61.17 km$^2$.

The southern coast of the study area was not affected by the tsunami. This is because the morphological form of these part is a cliff beach with a slope around 90° and the elevation around 30-170 meters. These results were similar with the statement from Robke and Vott [15], the steeper the slope, the lower the effect of the tsunami wave.

On the west coast, there were 2 medium and high tsunami inundation classes. Regions that have a moderate inundation class are strongly affected by the morphology form of the southern coast in Badung Regency which is cliffy so that the tsunami wave energy decreased due to wave refraction. While areas that classified as high inundation are still affected by wave refraction, but not significantly.
On the east coast, there are more complex classification of tsunami inundations. Areas that have high to very high inundation classes are affected by sloping coastal morphology and the absence of tsunami wave barriers to land. While areas that have a medium inundation class is affected by the existence of a coral reef ecosystem with shallow depth, so the waves broke before reaching the beach and the energy decreases.

CONCLUSIONS

Based on the results of an 8.3 Mw tsunami modeling simulation in the south of Bali Island, the wave travel time from the tsunami epicenter to the coast took 30–39 minutes. The wave height at the coast varies according to the observation point. The highest waves occurred at the Uluwatu observation point which reached 16.73 meters because it was located on the southern part of Bali Island and closer to the tsunami epicenter, while the observation points in Denpasar City and the northern coast of Badung Regency have relatively lower wave heights from 4.84–6.9 meters because the tsunami wave strength has been decreased at the southern point of Bali Island. The maximum inundation caused by the tsunami waves reached 15.5 meters with the coverage area in Denpasar City around 65.86 km² and Badung Regency around 61.17 km².

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