Numerical modelling for tsunami wave propagation (case study: Manado bays)

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Abstract. The north arm of Sulawesi is one of the most vulnerable areas of the earthquake and tsunami. This region is a meeting place for several tectonic plates such as the Indo-Australian Plate, the Pacific Plate, the Philippine Sea Plate and the Eurasian Plate. As a result, collisions of the plates, subduction zones are formed in this region. The North of Sulawesi subduction zone and Molluca double subduction zone are sources of earthquakes that can generate tsunamis in the region. This study aims to examine the potential tsunami hazard on the north coast of Sulawesi's northern arms specifically in the Manado bays. Data were collected from various tsunami catalogues and literature review to determine the input parameters. The modelling is done by using TUNAMI N2 software which is a tsunami modelling using shallow water wave theory. The simulation results show that the tsunami wave height that can hit the Manado beaches varies from about 1.5 to 3 meters, while the tsunami propagation time from the source to the beach is about 24 minutes after earthquake.

Keywords: Earthquake, Tsunami, potential, TUNAMI

1. Introduction

Indonesia is the third largest country in the world within 500 years, with a population of around 5.5 million people killed by the tsunami waves. Even within a hundred years Indonesia has been hit by at least 24 tsunamis with the lives of no less than 231,900 people [1]. As a country located in the seismic zone of Southeast Asia, Indonesia is one of the countries with the highest level of seismicity in the world [1][2]. This is because the territory of Indonesia is a meeting place for some of the world's large plates such as the Indo-Australian plate, the Pacific plate and the Philippine plate which are under the Eurasian plate.

One of Indonesia's with high seismicity regions is the northern arm of Sulawesi. The North Arm of Sulawesi Island is geologically a meeting point of several tectonics plates. North Arm of Sulawesi located between three plates: Eurasian Plate, the Pacific Plate, and the Indo-Australian Plate and a micro plate, the Philippine Sea Plate. As a result of the complexity of the movement of these plates resulted in the formation of Molluca sea double subduction and North Sulawesi Trench which could potentially cause medium to large earthquakes in megathrust zones which could trigger a tsunami. Historical tsunami data show that the area of the north arm of Sulawesi has been hit several times by the tsunami wave causing loss of life, devastating property and environmental damage [3].

Tsunami is an ocean waves that occur due to an impulsive undersea disturbance or activity near the coast or in the ocean, when a sudden displacement of a large volume of water occurs, or if the sea floor is suddenly raised or dropped by an earthquake, big tsunami waves can be formed. The waves travel out of the area of origin and can be extremely dangerous and damaging when they reach the shore. This exclusive disruption occurs due to sudden sea deformation, especially in the vertical direction. Deformation can be caused by three main sources, namely earthquakes, volcanic eruptions, and landslides on the seabed. In general, tsunamis are caused by earthquakes, where the vertical tectonic shift of the seabed along the fracture zones on the earth's crust causes vertical disturbance of the water body[1][4].

Mitigation efforts need to be done as early as possible. Tsunami disaster mitigation is one of them through tsunami modelling or simulation. Tsunami modelling is an effort to determine the spread of tsunami waves from a particular source mechanism, the time needed for a tsunami wave (travel time) from the trigger source to one of the coastal areas and tsunami height (run up) in the area affected by the tsunami wave. Predictions of the time of propagation and height of tsunamis on the coast are very important as input in making evacuation plans and maps, construction of sea walls on the beach, plans for development and development of coastal areas

2. Tectonics Setting of North Arm Sulawesi

The northern arm of Sulawesi is one of the regions that has a very high level of seismicity (Figure 1) when compared to other regions in Sulawesi Island. The last largest earthquake in the northern arm was occurred in 1996 with a magnitude of M7.9. The source of the earthquake in this region came from several sub-districts such as North Sulawesi subduction (Minahasa Trench), Moluccan sea double collisions, subduction of the Philippine sea plate, and several active faults on the mainland north of Sulawesi [3]

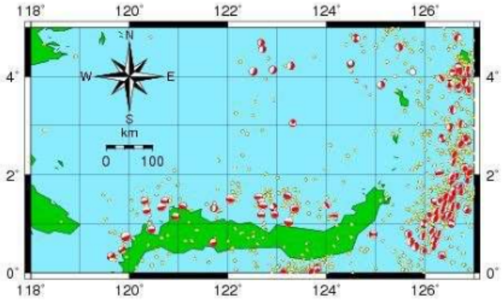

Figure 1. Seismicity Map and CMT Earthquake Focus Mechanism

Tsunami

Most tsunamis are caused by disturbances in the earth's crust on the seabed such as seabed earthquakes, landslides, or volcanic eruptions on the seabed causing rising water levels in large areas [5][6]. Tsunamis caused by earthquakes, where tectonic shifts in the vertical direction of the seabed along the fracture zones of the earth's skin cause vertical disturbances of the water body.

Shallow Water Equation

The tsunami wave propagation equation is approached by using a non-linear equation which is a shallow water equation [7]. Wave propagation model in shallow water is expressed by mass conservation / conservation equation and momentum equation in 3-dimensional cases as shown in equation (1).

$$\frac{\partial \eta}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho}\left(\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right)=0$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+\upsilon\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho}\left(\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right)=0$$

$$g+\frac{1}{\rho}\frac{\partial \rho}{\partial z}=0 \tag{1}$$

with x, y denotes the horizontal axis, z represents the vertical axis, t represents time, η states the vertical change in sea water immediately after the disturbance, h is the depth of sea water, u, v and w represent the velocity of the water particle in the direction of the x, y and z axes, g is the gravitational acceleration of the earth[7][8].

Tsunami wave propagation modeling is divided into two, namely near field tsunami and far field tsunami. In far field the tsunami uses a spherical coordinate system while near field tsunami is approached using a Cartesian coordinates system. This study used near field tsunamis so that in tsunami wave propagation modeling uses Cartesian cooperatives. The use of equations in Cartesian coordinates is based on the assumption of the shallow-water theory which states that the vertical acceleration of water particles is negligible when compared to gravitational acceleration except for the distribution of tsunamis in the ocean. We can solve the tsunami wave propagation problem by using equation (1) on boundary conditions. Kinetic and dynamic boundary conditions on the surface and at the base are given with the terms:

$$p=0 \quad \text{at } z=\eta \tag{2}$$

$$w=\frac{\partial \eta}{\partial t}+u\frac{\partial \eta}{\partial x}+v\frac{\partial \eta}{\partial y} \quad \text{at } z=\eta \tag{3}$$

$$w=-u\frac{\partial h}{\partial x}-v\frac{\partial h}{\partial y} \quad \text{at } z=-h \tag{4}$$

The dynamic and kinetic conditions of the equation (2)-(4) above finally obtained the nonlinear equation of movement (conservation of momentum) and the continuity equation (conservation of mass) in 2 dimensions (also called by shallow water wave theory):

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{\tau_x}{\rho}=A\left(\frac{\partial^2 M}{\partial x^2}+\frac{\partial^2 M}{\partial y^2}\right)$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{\tau_y}{\rho}=A\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right) \tag{5}$$

where D is the total water depth of h, $h+\eta$, η_x and η_y are the basic friction in the direction of the x and y axes, A is the eddy viscosity in the horizontal direction which is assumed to be constant and the shear stress (movement due to wind) on the surface is ignored. M and N are components for releasing water mass flux in the direction of the x and y axes stated in the equation:

$$M=\int_{-h}^{\eta} u\,dz=u(h+\eta)=uD$$

$$N=\int_{-h}^{\eta} v\,dz=v(h+\eta)=vD \tag{6}$$

A tsunami moves at the same speed as the square root of the product of the multiplication between the gravitational acceleration of the earth and the depth of the sea [8][9]:

$$v = \sqrt{gh} \tag{7}$$

where:
$\boldsymbol{v}$ = tsunami propagation speed (m/s)
g = gravity acceleration (m/s^2)
h = sea depth (m)

Each tsunami produces inundation and run up that vary according to energy and several factors such as coastline, bathymetry and coastal slopes

3. Methodology

The simulation uses a shallow water wave theory model in shallow sea. The simulation uses the help of the TUNAMI N2 (Tohoku University's Numerical Analysis Model for Investigation of near Field Tsunami software, number 2). TUNAMI N2 is a tsunami modeling that uses a leap-frog scheme [7]. This application uses tsunami generator source parameters based on the analysis of potential earthquake energy. The next step is to determine the area to be modeled using the nested grid method. The modeled area is then divided into several spatial resolutions (layers), each layer will be divided based on the tsunami generation area and the tsunami affected area. The widest area of work is layer 1 and is narrowing down to the extent of the layer located within it. In this study used four layers of each scenario.

The next stage of the research is to create a scenario using the source of the tsunami generator, namely the subduction of North Sulawesi (North Sulawesi subduction). The earthquake hypocenter is assumed to occur in the megathrust area or at a depth of less than 50 km. The North Sulawesi subduction consists of two segments namely the west and east segments. In this scenario using two segments at once namely the east and west segments as a tsunami generator.
Tsunami generation and propagation due to earthquakes with different fault parameters were studied. This scenario requires data such as strike, dip, slip, length and width of the fault with earthquake mechanisms interpreted in source parameters as presented in Table 1 below:

Table 1. Source Parameter

Parameter	Scenario 1	Scenario 2
Longitude	120,735	121,558
Latitude	1,879	2,29
L (m)	100 km	200 km
W (m)	60 km	60 km
Strike	60	100
Dip	20	20
Slip angle	85	85
Depth	10 km	10 km

The next step is to collect depth or bathymetry data from GEBCO (30 arcseconds) and 1 arcsecond SRTM Digital Elevation Model (DEM) topography data from USGS. The simulation results in the form of snapshots are displayed for 1 minute intervals, with a simulation time of 60 minutes (3600 seconds) after the earthquake. A minute wave that describes the time of arrival of a tsunami wave (travel time) and the tsunami wave height (run up) is obtained based on a predetermined parameter.

4. Discussion

Modeling results in the form of snapshots per minute which describe the time of propagation of tsunami waves (travel time) and tsunami height (run up) on each layer are explained as follows.

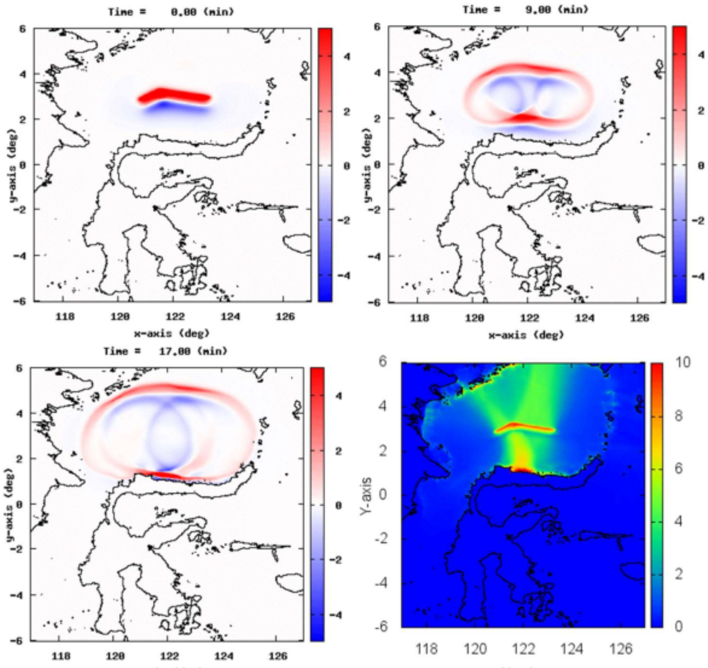

Figure 2. Visualization of tsunami wave propagation in the North Arm Sulawesi at 0 minute, 9 minute, 17 minute and maximum run up

From Figure 2 above it shows that shortly after the earthquake when t = 0 minutes most of the coastal area especially Tolitoli Regency, Gorontalo North Coast and North Bolaang Mongondow experienced a decrease in water level / low tide (blue). Likewise at t = 4 minutes the water still recedes to the large part of the north coast but once entering the 16th minute there is an increase in water level (red). From the simulation large maximum water levels ranging from 6-10m found along the northern coastline Buol Regency, Central Sulawesi.

The along north coast of Sulawesi's northern arm show the tsunami wave is expected to hit at 16-24 minutes after earthquakes. Especially the Manado Bay area is predicted that a tsunami can occur in the 24th minutes (Figure 3) after earthquake with the water level maximum is 1.5-3m. The water level maximum can greater than 3m due to amplification of tsunami waves that occur in the bay region.

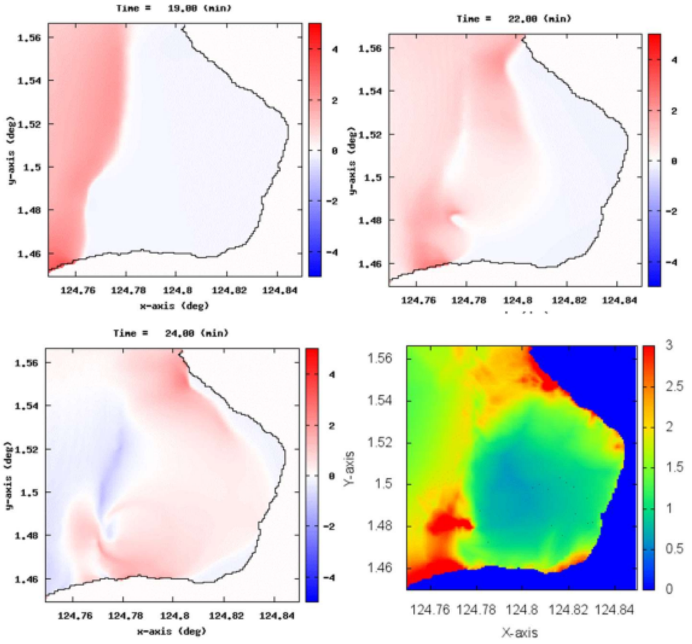

Figure 3. Tsunami wave propagation at layer 4 for 19 minutes, 22 minutes, 24 minutes and maximum run up on Manado Beach

The simulation results in Figure 3 are the same as the previous picture, but in this condition the area is smaller so that the affected area specifically can be seen more clearly. From the picture it can be seen that the high level (run up maximum) of tsunami waves that can occur in Manado bays is around 1.5-3 meters

To see clearly what the height of the tsunami in some places on the Manado coast, there are several Tide Gauges (TG) which are shown in the following Figure 4.

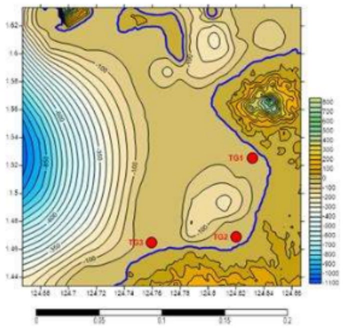

Figure 4. Positioning of Tide Gauges (TG)

The recording results for each Tide Gauge are the tsunami propagation time and wave height as shown in the following Figure 5.

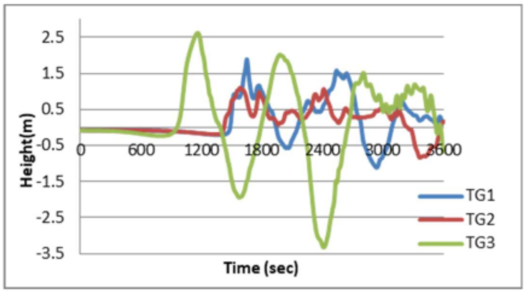

Figure 5. Time Series of Manado Bays Tsunami Wave Propagation, shows the location of each Tide Gauge

5. Conclusion

This model successfully simulates the propagation of tsunami waves due to earthquakes in North Sulawesi using the TUNAMI-N2 model. The northern coast region of the north arm Sulawesi is very vulnerable to the tsunami disaster. The height of the tsunami that can occur in this region is around 1-10 meters. Especially for beaches Manado bays the tsunami wave period ranges from 20 to 24 minutes after an earthquake with a height of around 1.5-3 meters. This tsunami height can be greater than 3 meters considering that the Manado beach is in the shape of a bay where tsunami wave amplification can occur.

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