

TSUNAMI HAZARDS ALONG COASTAL AREA OF WEST KALIMANTAN PROVINCE, INDONESIA

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ABSTRACT: This study aims to simulate tsunami wave heights and their travel time toward the West Kalimantan coastal area. A Nuclear Power Plant (NPP) will be developed in a coastal area in the West Kalimantan Province, Indonesia. The two scenarios of events that may trigger the tsunami waves are volcanic events caused by Mount Krakatau located in the Sunda Strait and tectonic subduction located at the Indian Ocean on the west side of the Sunda Strait. Modeling the tsunami propagation using a finite-element-based hydrodynamic model developed by the US Army Corps of Engineer, namely the Surface-water Modeling System (SMS), is carried out. The model simulates tsunami wave propagation for six alternative locations at the proposed site of NPP. The model domains consist of Sunda Strait and Karimata Strait domains. The Sunda Strait domain model is validated by the observed historical tsunami heights reaching the 12 locations in Lampung, Banten, West Java, and Jakarta of Indonesia. The model validations show a good agreement. The validated hydrodynamic model results of the Sunda Strait model are used as the boundary conditions for the Karimata Strait domain model. The Karimata Strait model results show that the peaks of tsunami wave heights that reach the western Kalimantan coast are between 12 cm and 116 cm. The minimum wave height peak that reaches the six prospective locations is 12 cm, which is located in Sambas Regency.

Keywords: Sunda Strait, Tsunami Hazards, Numerical modeling, Krakatau, Tectonic

1. INTRODUCTION

Two-thirds of greenhouse gases (GHGs) arises from the energy sectors, not only in production but also in consumption [1]. The nuclear power plant and the other renewable energy-sourced power plants are expected to be solutions to the GHGs [2]. Nuclear fusion-based energy is shown to mitigate carbon emissions potentially [3, 4].

There are 438 units of Nuclear Power Plant (NPP), which are operating in 30 countries among the developed and developing countries until the year 2010. The NPP is contributing up to 18% of the world's energy supply [5]. Furthermore, Indonesia has also studied to utilize the NPP in West Kalimantan Province [6]. There are some parameters that are required to be considered in the determination of the proposed site. Among them are the surrounding ocean aspects, such as water depth, tidal, waves, current, and tsunami risk [7].

Additional studies on tsunami prevention arose when the Tohoku Earthquake and Tsunami, Japan, occurred in 2011. The giant earthquake and tsunami impacted the NPP facilities area within the 230 km stretch of coastline. The 14-meter tsunami waves hit the Fukushima Dai-ichi facilities, causing a loss of power and extensive radioactive contamination [8, 9]. The scenarios in tsunami modeling become invaluable in the mitigation of the disaster impact [10].

Giant tsunami events have also occurred in Indonesia several times, including the 2004 Indian Ocean and the 2018 Sulawesi earthquakes and tsunamis. The 2004 Indian Ocean earthquake and tsunami swept the Aceh Province [11,12]. The 2018 Sulawesi earthquake and tsunami have also been studied [13].

In this study, the tsunami wave heights caused by potential volcanic and tectonic events is carried out using finite element-based numerical modeling for the proposed NPP in the West Kalimantan Province. Some previous studies used software tools, such as Delft3D [11-13], FVCOM [14], Anuga [15], MIKE [16], and Volcflow [17]. The current research uses the RMA2 module of the Surface-water Modelling System (SMS) to model the tsunami wave propagation toward the proposed site coastal line. This study provides the values of tsunami wave heights in six alternative locations of the NPP. The tsunami event is assumed to be triggered by the volcanic event caused by a Mount Krakatau eruption and tectonic subduction in the Indonesia Ocean adjacent to the Sunda Strait.

2. STUDY LOCATION

An NPP development is proposed in the province of West Kalimantan, Indonesia. The local government has proposed six alternative locations [7]. They are (1) Air Besar Village, Ketapang Regency, (2) Sie Village, North Kayong Regency,

(3) Sungai Kanan Village, Ketapang Regency, (4) Sungai Nanjung Village, Ketapang Regency, (5) Kendawangan Village, Ketapang Regency, and (6) Matang Village, Sambas Regency. Figs. 1(a) and 1(b) show the locations of six alternative NPP sites that face the Karimata Strait. The locations of the tsunami sources are given in Fig. 1(c). They are the Indian Ocean megathrust in the western Sunda Strait (termed as the “tectonic source”), and the volcanic submarine landslides due to an eruption of Krakatau (denoted as “volcanic source”).

3. METHODOLOGY

A finite-element-based software developed by the US Army Corps of Engineers, namely the SMS, has become the research tool to model the hydrodynamics of tsunami waves propagation [18]. RMA2 is a module within the SMS that simulates current velocities and water surface elevations. The module simulates the depth-averaged current velocities. This program has been widely used for a variety of hydrodynamic studies in coastal areas [19], rivers [20], or lakes [21, 22].

3.1 Governing Equations

The governing equations are the conservation of mass and momentum equations, which are depth-averaged. Vertical direction acceleration is ignored so that the velocity vector has the same magnitude and direction along the water column. The depth-averaged velocity U used in RMA2 is written in Eq. (1). The governing equations are given in Eqs. (2) - (4). Equation (2) is the continuity equation and Eqs. (3) and (4) are the x and y-direction of momentum equations, respectively.

$$U = \frac{1}{h} \int_0^h u(z) dz \quad (1)$$

$$\frac{\partial h}{\partial t} + h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \quad (2)$$

$$h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - \frac{h}{\rho} \left[E_{xx} \frac{\partial^2 u}{\partial x^2} + E_{xy} \frac{\partial^2 u}{\partial y^2} \right]$$

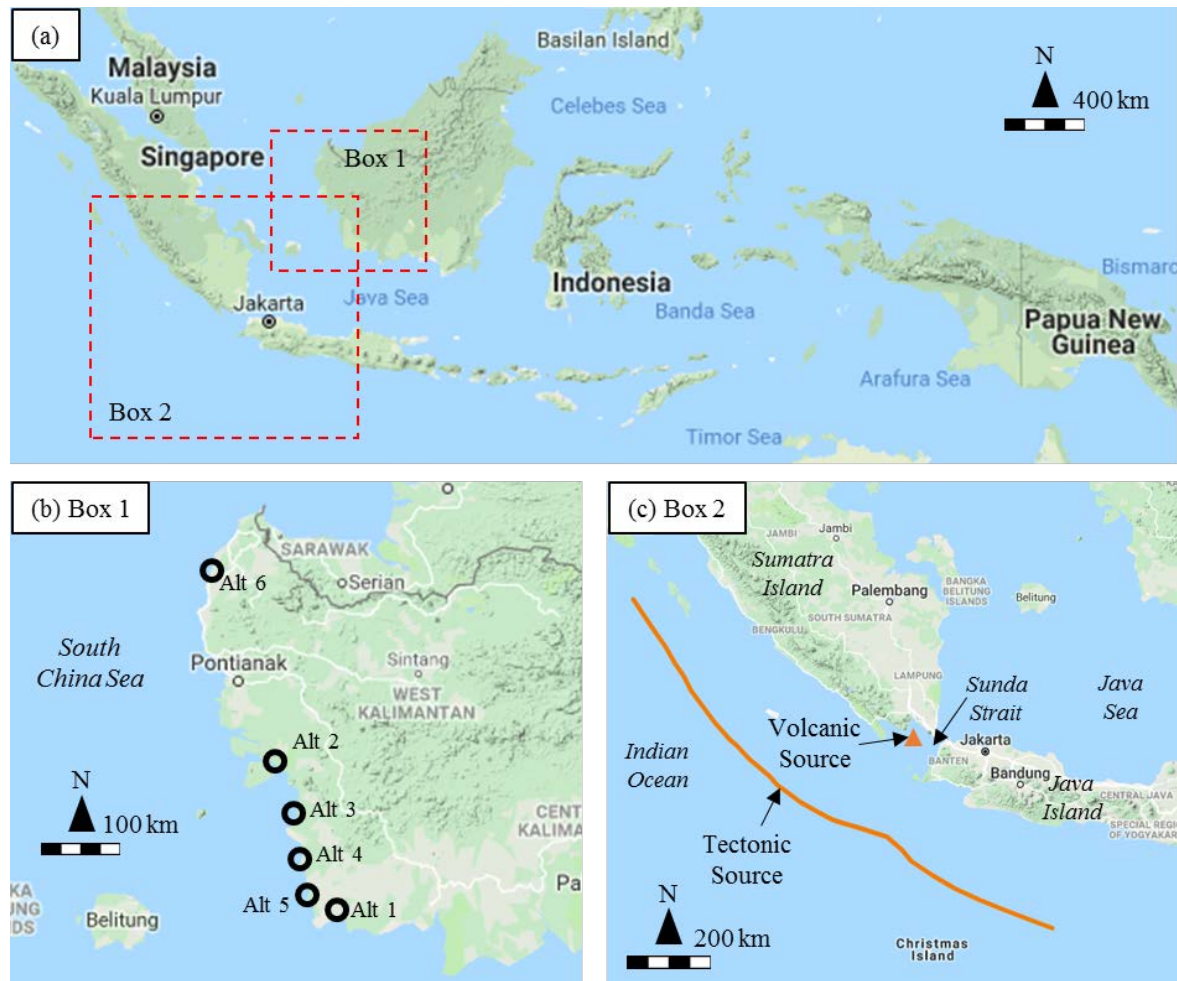


Fig. 1 (a) Overview of Indonesia, (b) six potential locations for Nuclear Power Plant in West Kalimantan, and (c) the tsunami sources consist of volcanic and tectonic sources.

$$\begin{aligned}
 & +gh \left[\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right] + \frac{gun^2}{\left(1.486h^{1/6} \right)^2} \left(u^2 + v^2 \right)^{1/2} \\
 & -\zeta V_a^2 \cos \psi - 2hv\omega \sin \Phi = 0 \quad (3) \\
 & h \frac{\partial v}{\partial t} + hu \frac{\partial v}{\partial x} + hv \frac{\partial v}{\partial y} - \frac{h}{\rho} \left[E_{yx} \frac{\partial^2 v}{\partial x^2} + E_{yy} \frac{\partial^2 v}{\partial y^2} \right] \\
 & +gh \left[\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y} \right] + \frac{gvn^2}{\left(1.486h^{1/6} \right)^2} \left(u^2 + v^2 \right)^{1/2} \\
 & -\zeta V_a^2 \sin \psi + 2hu\omega \sin \Phi = 0 \quad (4)
 \end{aligned}$$

The x, y, z are Cartesian coordinates. h is the water depth. t is time. u and v are velocities in cartesian coordinates. U is the depth-averaged velocity in the x -direction. E is the eddy viscosity coefficient. ρ is fluid density. a is the elevation of the bottom. g is the gravitational acceleration. n is the Manning's roughness n -value. ζ is the empirical wind shear coefficient. V_a is the wind speed. ψ is the wind direction. Φ is the local latitude. ω is the rate of angular rotation of the Earth, and 1.486 is the conversion from SI to non-SI units.

3.2 Model Setup

The tsunami wave model is set into two domains, namely the Sunda Strait domain (source domain, where the sources of the tsunami are located) and the Karimata Strait domain. The purpose of the use of two domains is to improve accuracy and streamline modeling. The hydrodynamic results in the source domain are

validated using the observed tsunami waveforms at Jakarta and tsunami wave heights along the coasts of Java and Sumatra [23, 24]. The hydrodynamics results from the source domain will be used as boundary conditions for the Karimata Strait model. The two domains can be seen in Figs. 2 and 3. The bathymetric data used in this modeling is a navigational chart issued by the Indonesian Navy's Hydro-Oceanographic Agency, the year 2012 [25].

The scenarios for the model are based on the tsunami source. Scenario-1 represents volcanic explosions of Mount Krakatau as the source, denoted by "volcanic." Scenario-2 is the tectonic subduction off-coast of Sumatra Island adjacent to the Sunda Strait, denoted by "tectonic." For both volcanic and tectonic model scenarios, a positive initial displacement is used, forming a dome of water at the source and is propagated over the bathymetric data [24].

3.3 Model Validation

The comparative data for the validation is the field observation of tsunami heights [23], and the results of previous studies [24]. In the previous study, the authors used the nonlinear shallow-water wave theory to the tsunami wave propagation due to the eruption of Krakatau in 1883. They proposed three models: 1) large scale caldera collapse; 2) emplacement of pyroclastic deposits; 3) submarine explosion. In the present study, an initial displacement in the form of a water wave with a certain height is placed in the location of the source. The wave is propagated and validated upon reaching the coastal line. This initial displacement is iterated until the computed propagated waves

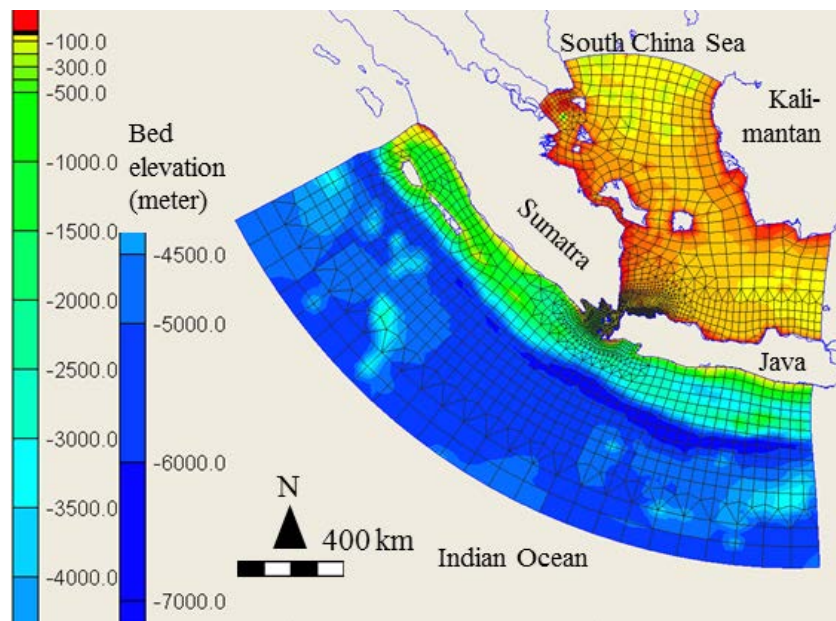


Fig. 2 Sunda Strait or source domain.

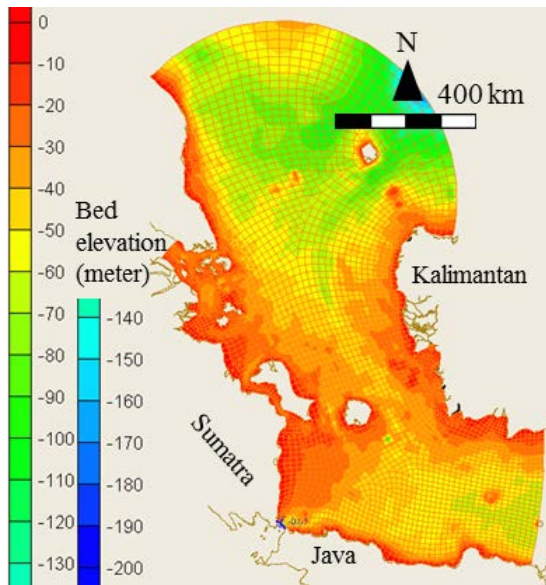


Fig. 3 Karimata Strait domain.

match the observed values. After several trials, the initial water displacement of 4 meters at the center of the volcanic tsunami (Figs. 4(a) and 4(b)) gives proper validation with observed data and previous

studies.

Two methods are used in the validations; they are the maximum wave height at 12 locations and a time series of water level elevation in one location. The 12 validation locations are shown as points in Fig. 4(b), namely Tanjung Belimbing (Blb), Bandar Lampung (BL), Kalianda (Kal), Panaitan Island (Pan), Labuan (Lab), Anyer (Any), Merak (Mer), Banten (Ban), Lontar (Lon), Karawang (Kar), Tangerang (Tan), and Thousand Islands (Srb). The results of the comparison of the maximum wave height between the model and the comparable data at the 12 points are presented in Fig. 5. Three locations are reviewed in Table 1, namely, Bandar Lampung (BL), Labuan (Lab), and Merak (Mer), locations are shown as red dots in Fig. 4(b). The time series of these locations are given in Fig. 6. From Fig. 5 and Table 1, it is found that the wave height between the model and the comparative data shows a good match.

The second validation method is the comparison between the observed time series of water level in Batavia, denoted by a blue point in Fig. 4(b) (now Jakarta), with the model results. The results of the comparison are given in Fig. 7. The amplitude and time of occurrence of peak and trough waves are

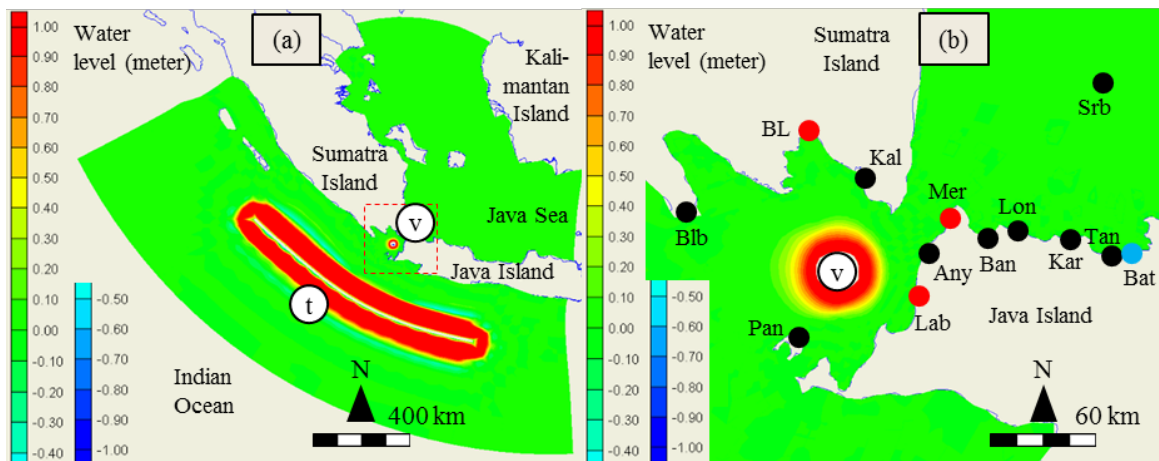


Fig. 4 (a) Source of volcanic-v and tectonic-t tsunami wave model and (b) 13 observation locations for validation for volcanic-v tsunami model.

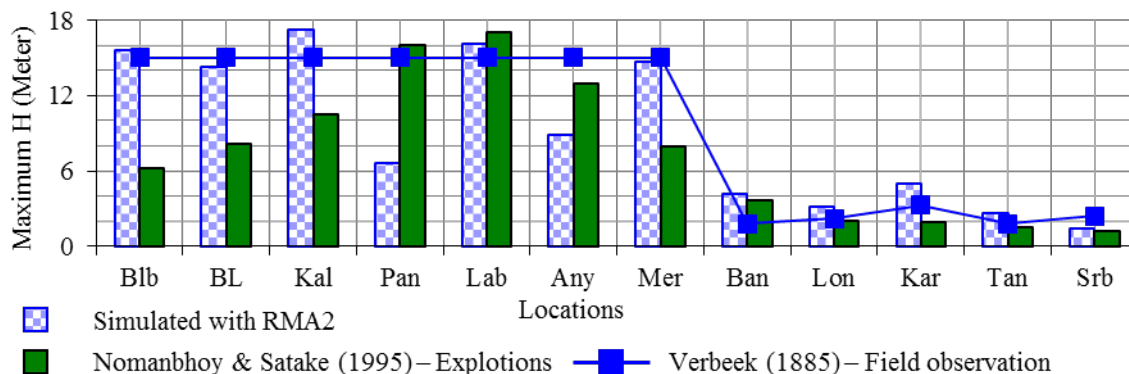


Fig. 5 Comparison of peak wave height between the RMA2 model, Nomanbhoy & Satake (1995), and observation by Verbeek (1885) at 12 locations.

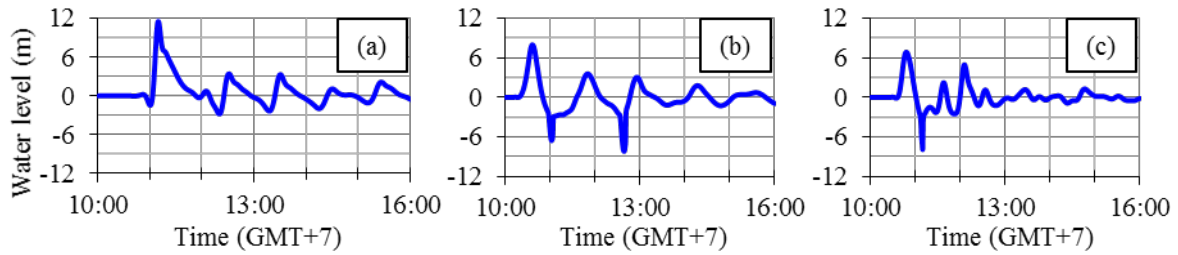


Fig. 6 Time series of water level at (a) Bandar Lampung - BL, (b), Labuan - Lab and (c) Merak - Mer

given in Table 2. Of the two validation methods performed, it is found that the amplitude and time series of the modeling results agree well with the comparative data. From this validation, the Sunda Strait model results are considered reliable so that further tsunami modeling can be carried out for the Karimata Strait domain. For the discussion, the simulation of tsunami wave propagation due to tectonic activity in the Indian Ocean is carried out using the initial water displacement of 10 m at the tectonic source. For the present study, there is no data available yet for validation of the tsunami wave model due to the Sunda Straits megathrust earthquake. The tectonic source tsunami model uses the same parameters as in the volcanic source tsunami model.

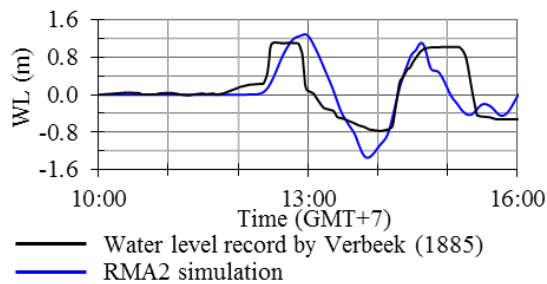


Fig. 7 Water level and arrival time validation at Batavia.

Tables 1 and 2 are the data obtained from the previous researchers who are adapted to the current study. The current model is considered valid based on these previous results.

Table 1 Detailed water level validation at Bandar Lampung, Labuan, and Merak.

| Location | RMA2 (m) | *Flow (m) | **Field Obs (m) | Error (%) |
|----------------|----------|-----------|-----------------|-----------|
| Bandar Lampung | 14.3 | 8 | 15 | 4.6 |
| Labuan | 16.2 | 6.4 | 15 | 7.1 |
| Merak | 14.7 | 7.4 | 15 | 1.8 |

*Flow: pyroclastic flow deposit model [24]

**Field Obs: Field observation [23]

Table 2 Detailed water level and arrival time validation at Batavia

| Parameter | RMA2 | **Field Obs. |
|---------------------------------------|-------|--------------|
| Peak elevation (meter) | 1.28 | 1.11 |
| Lowest elevation (meter) | -1.34 | -0.76 |
| Period (hour) | 1.59 | 2.26 |
| Wave crest 1 st (o'clock) | 12.58 | 12.42 |
| Wave trough 1 st (o'clock) | 13.51 | 14.01 |
| Wave crest 2 nd (o'clock) | 14.38 | 14.45 |

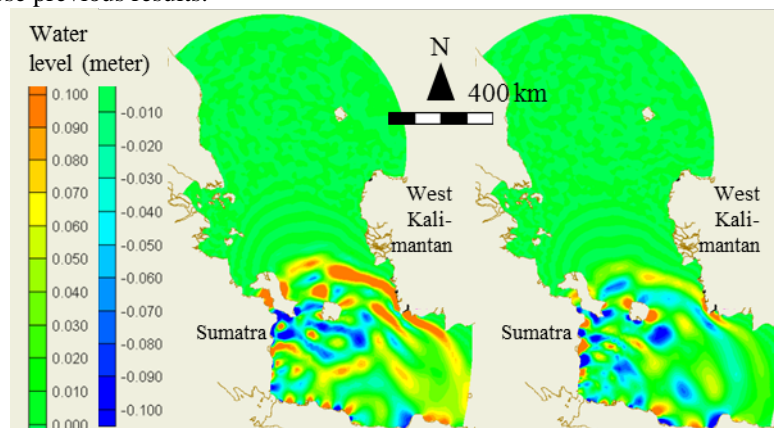


Fig. 8 Spatial water level distribution for (left) volcanic and (right) tectonic sources.

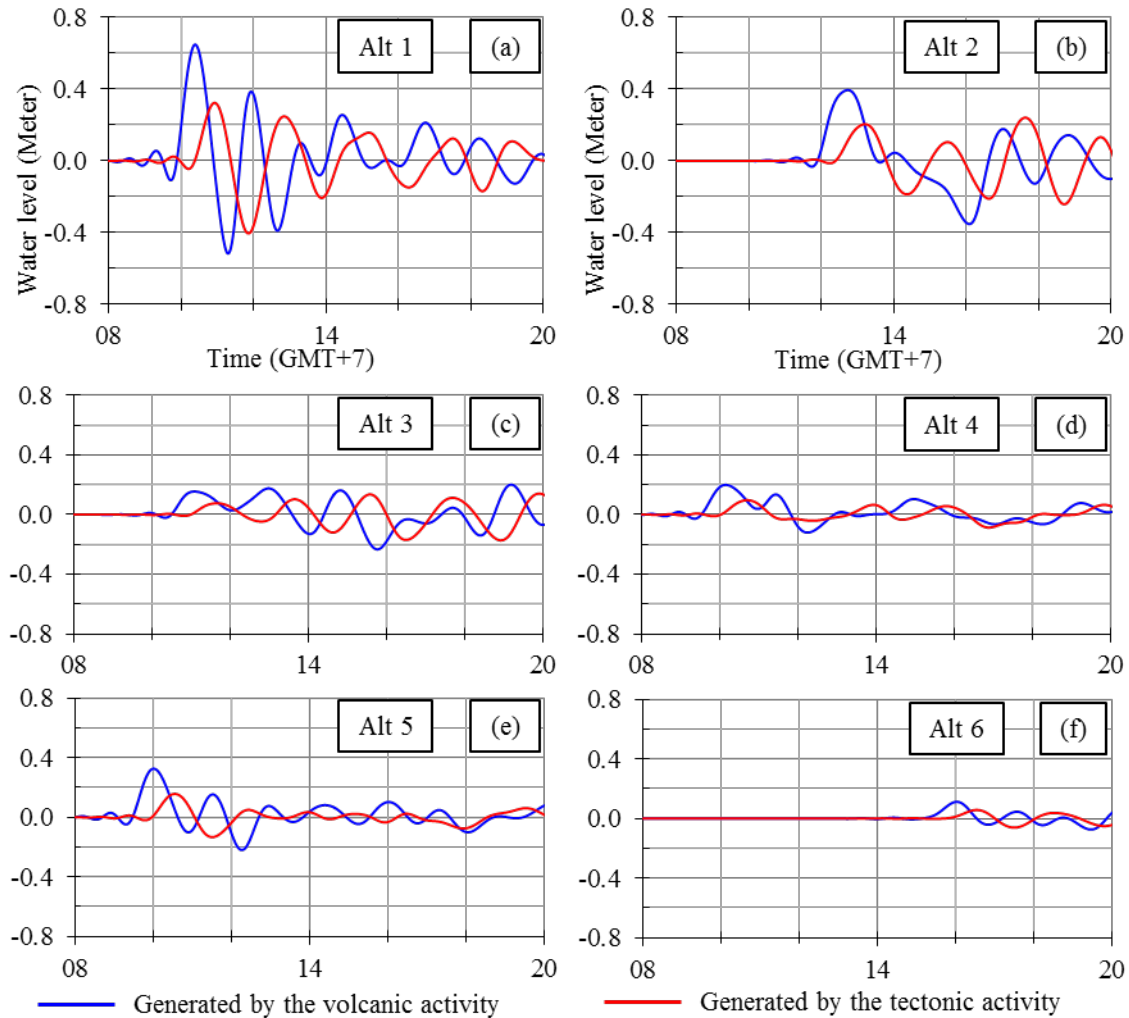


Fig. 9 Time series of water level at six alternative locations.

4. DISCUSSIONS

The simulation of the propagation of tsunami waves due to volcanic activity in the Sunda Strait and tectonic activity in the Indian Ocean has been carried out. The tsunami wave heights reaching the potential sites of NPP proposed sites in the coastline of West Kalimantan Province has been obtained. The simulation results of the Karimata Strait domain can be seen in Fig. 8 (left) for volcanic-induced tsunamis and Fig. 8 (right) for tectonic-induced tsunamis. Fig. 8 shows the tsunami water level at the coast of West Kalimantan. The tsunami waves at this location are coming from the southwest. The time-series graph of the water level elevation in the six alternative locations can be seen in Fig. 9(a) to 9(f), respectively. The time-series graph summary for the six alternative NPP locations is given in Table 3.

The volcanic activity of Mount Krakatau produces more considerable wave heights for all six potential regional locations for the NPP. The maximum tsunami wave height of 1.16 meters

occurs at Alt. 1 – Ketapang Regency, while the lowest maximum wave height is 0.12 meters and occurs at Alt. 6 – Sambas Regency.

Table 3 Maximum tsunami wave height at six alternative locations.

| No | Location | Wave height (m) | |
|----|----------|-----------------|----------|
| | | Volcanic | Tectonic |
| 1 | Alt 1 | 1.16 | 0.73 |
| 2 | Alt 2 | 0.75 | 0.50 |
| 3 | Alt 3 | 0.43 | 0.31 |
| 4 | Alt 4 | 0.32 | 0.18 |
| 5 | Alt 5 | 0.55 | 0.29 |
| 6 | Alt 6 | 0.19 | 0.12 |

5. CONCLUSIONS

Regions that have the smallest tsunami wave height are the areas with the most potential to become the NPP sites. Sambas Regency (denoted by Alt. 6) has the smallest value of 0.19 meters for volcanic tsunamis and 0.12 meters for tectonic tsunamis. The tsunami wave height in potential locations caused by volcanic activity is relatively higher compared to tectonic activity. The distance to the source is a determining factor in the propagation of tsunami waves.

As explained in the introduction section, tsunami risk is only one of several parameters for assessing the site of NPP development. Some other parameters should also be studied, including seawater depth, tidal, waves, and current conditions. Alt. 6 is exposed to a long fetch from the South China Sea, so there is a potential for high ocean waves to attack the site. For further research, other parameters will be studied to determine the most appropriate location for the site of an NPP.

The implementation of this study to the community surrounding the proposed NPP area would be the consideration of all aspects of tsunamis and the above-mentioned environmental hydro-oceanographic conditions to a mitigation scheme of all infrastructures and people to avoid the risk. The mitigation plan is carried out and promoted by the local government.

The next research should be the modeling of the tsunami waves due to the subduction of the tectonic plates in the South China Ocean, north of the current NPP proposed site.

6. ACKNOWLEDGMENTS

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