

Original Article

e-ISSN: 2581-0545 - <https://journal.itera.ac.id/index.php/jsat/>



Towards Comprehensive Tsunami Mitigation Study: a Case of Legundi Island

Received 30th January 2021
Accepted 21th May 2021
Published 1st July 2021

Open Access

DOI: 10.35472/jsat.v5i2.408

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Abstract: The 2018 Sunda Strait Tsunami was driven to a flank collapsed of *Gunung Anak Krakatau* (GAK). Lampung Province was affected by Sunda Strait Tsunami at various locations that close to GAK. The research is about comprehensive mitigation by combining the wave model and tsunami perspective studies in Legundi island. There are four scenarios for wave modelling, and all scenarios are considered from the former study about Sunda Strait Tsunami 2018. The wave model produces the inundation height in the island is 3.34 m which leads to an error of less than 1% compared to the measurement data. The model shows a satisfactory result and can be a good approach for another wave modelling in other locations. The travel time of tsunami is estimated at around 30 minutes which also defines available evacuation time. The island will have a lower risk of an extreme event like a tsunami if the early warning system and evacuation route are designed for the residents. Therefore, installing a tsunami early warning system and providing regular tsunami drilling programs for locals will prevent more damages on this island.

Keywords: tsunami, wave modelling, mitigation study, Legundi island

Introduction

Sunda Strait tsunami that occurred in December 2018 was convincingly driven by a flank collapsed of *Gunung Anak Krakatau* (GAK) ([1,2]). Lampung was one of the affected provinces by the Tsunami. The research was conducted at a specific island in the Sunda Strait water area between GAK and Lampung mainland, namely Legundi Island, as shown in **Figure 1**. The research aims to get a comprehensive study of mitigation plan based on wave model and tsunami perspective of local people.

Sunda Strait Tsunami 2018 was categorized as a volcano/landslide tsunami, which occurred in less than 20% of all recorded events [3]. This tsunami was not induced by tectonic movement, but due to a flank collapse of mountain bodies, it was the reason why this tsunami was unique. Wave modelling of Sunda Strait Tsunami 2018 analyses how the wave is transformed in the bay [4]. A questionnaire survey is done to interpret local citizen perspective and experiences during tsunami [5].

Method

Wave transformation modelling in the bay was conducted by using SwanOne. The field measurement was taken in the research area, Legundi Island. The distance from the coastline to the offshore boundary was about 1 km. In the modelling, the input is provided by field measurement data. For instance, the bottom profile input was from the bathymetric contour map of the research location to define the coastline and the sea. Boundary and initial conditions are the parameters to make some wave modelling scenarios, such as wave height and period in the offshore side of the bay. The software will handle the computation and produce graphs of wave heights, wave period, wave direction, wave setup, and water depth in the bay's nearshore side.





Figure 1. Inundation height and run-up position of the tsunami in Legundi island



Figure 2. A fishing boat was washed away to the land on Legundi island

[1,6,7,8,9] conducted researches about inundation/run-up heights at various locations along the coast of Lampung and Banten. The tsunami inundation height of Legundi Island is 3.38 m with a run-up distance reach 200 m from the coastline. People are fully aware of the tsunami's dangerous effects; however, they were not prepared and confused about mitigating.

The questionnaire survey was carried out through an interview with victims of the 2018 Sunda Strait Tsunami. The questionnaire was designed to obtain various essential information to determine the awareness and preparedness of the Legundi Island community, including demographics of victims, sources of tsunami knowledge, evacuation behaviour, and post-disaster. This survey was conducted on Legundi Island, precisely in Selesung 1 & 2 Villages.

Tsunami Mitigation Plan in this island combines the wave model study and the resident's tsunami perspectives study to get a comprehensive design. The framework of this research method is shown below in **Figure 3**.

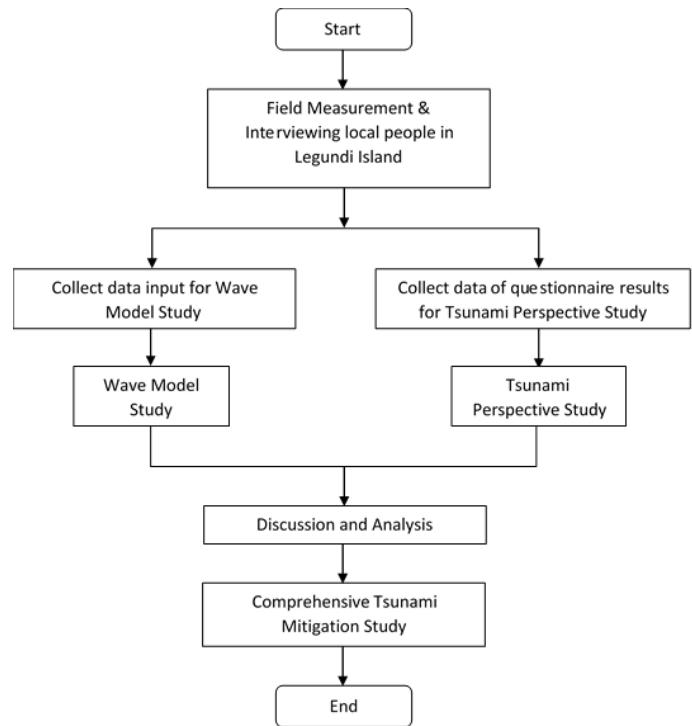


Figure 3. Flowchart of comprehensive tsunami mitigation study

Wave Model Study

Figure 4 is the bathymetry contour map from field measurement. A bathymetric survey was conducted in the nearshore of Selesung Bay (Legundi Island), $5^{\circ}48'00''$ S and $105^{\circ}18'14''$ E. Garmin GPSMAP 585 Plus is applied on a 5 GT boat. The sounding result was interpolated and calibrated with tides from the Agency of Geospatial Information (BIG) of Indonesia. The bathymetric survey development showed that the offshore boundary had -18.60 m depth and is located 882 m from the land boundary. The offshore border was used to define the bottom profile in wave modelling.

The wave model study in this research is using SwanOne Software. SwanOne is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. It assumes that the offshore bathymetry can be modelled such as bottom profile and can be specified along one transect normal to the coastline. The wave model represents the wavefield in terms

of wave spectrum, which then evolves towards the coast, including current, wind, depth, water level, shoaling, and refraction effects [12].

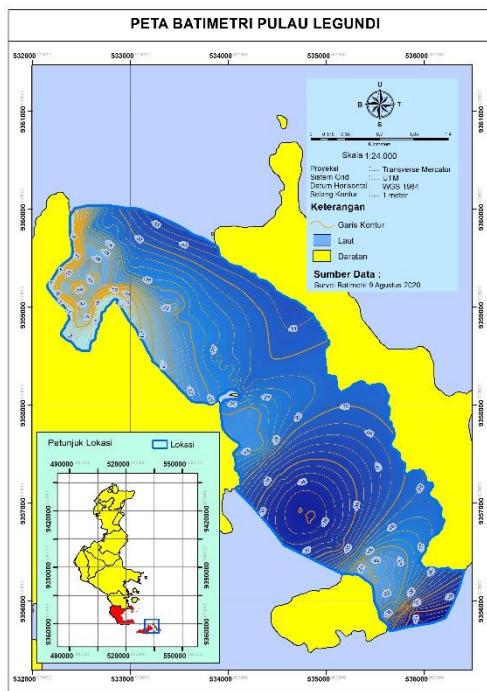


Figure 4. Bathymetry contour map of Legundi Island

After defining the bottom profile, set the boundary conditions regarding the four scenarios for this research. See **Table 1.** to know what parameters of boundary conditions changed to produce significant results.

Table 1. Scenario for wave modelling in SwanOne

Parameters/Scenario	1	2	3	4
Wave Spectrum	1D Jonswap	1D Jonswap	1D Jonswap	1D Jonswap
Water Set-Up	Yes	Yes	Yes	Yes
Wind Speed	10 m/s	10 m/s	10 m/s	10 m/s
Wave Height	1 m	3 m	3 m	2 m
Wave Period	300 s	50 s	30 s	10 s

Tsunami wave modelling applies a principle of nearshore wave transformation. For a water channel without any structures in the bay, shoaling and refraction exist [10,11,12]. Shoaling and refraction evolve the wave height and the direction along the bay. The wave propagating over a bathymetry with a gentle slope and no currents, the dispersion relationship remains as follow,

$$\omega^2 = gk \tanh(kd) \quad (1)$$

In which,

$$\omega = \frac{2\pi}{T} \quad (2)$$

$$k = \frac{2\pi}{L} \quad (3)$$

The above equations were re-formation, and it will produce the wave phase speed and group velocity as a function of depth as follow,

$$c = \sqrt{\frac{g}{k} \tanh(kd)} \quad (4)$$

$$c_g = nc \text{ with } n = \frac{1}{2} \left(1 + \frac{2kd}{\sinh(2kd)} \right) \quad (5)$$

Assuming the tsunami waves is long enough hence,

$$\tanh(kd) \rightarrow kd \text{ for } kd \sim 0 \quad (6)$$

$$c = \sqrt{gd} \quad (7)$$

$$t = \frac{S}{c} = \frac{S}{\sqrt{gd}} \quad (8)$$

The estimated travel time (t) of a tsunami reaching the island is around 30 minutes based on the governing equations and available data.

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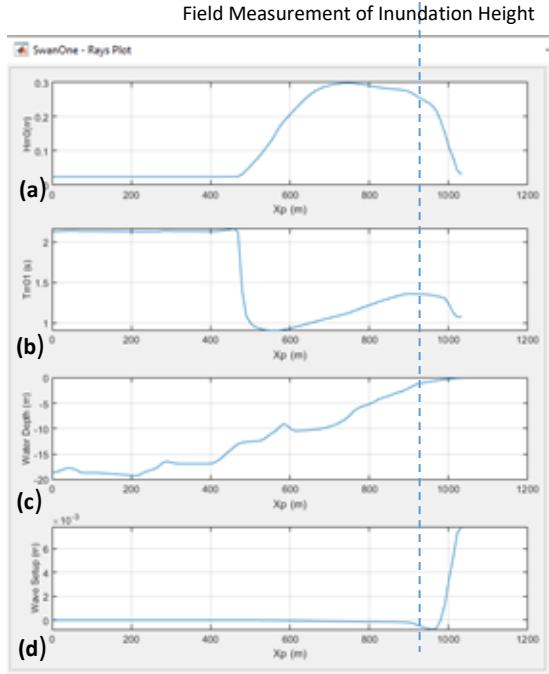


Figure 5. Results of Scenario 1, (a) Wave Height, (b) Wave Period, (c) Water Depth, (d) Wave Setup

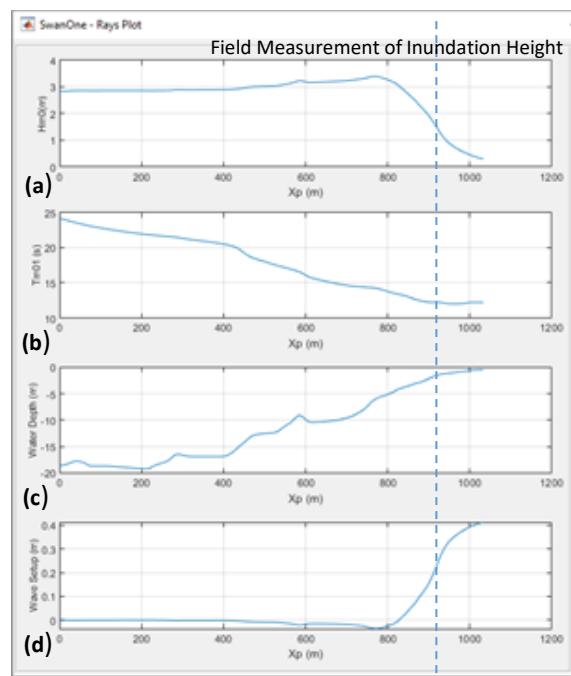


Figure 7. Results of Scenario 3, (a) Wave Height, (b) Wave Period, (c) Water Depth, (d) Wave Setup

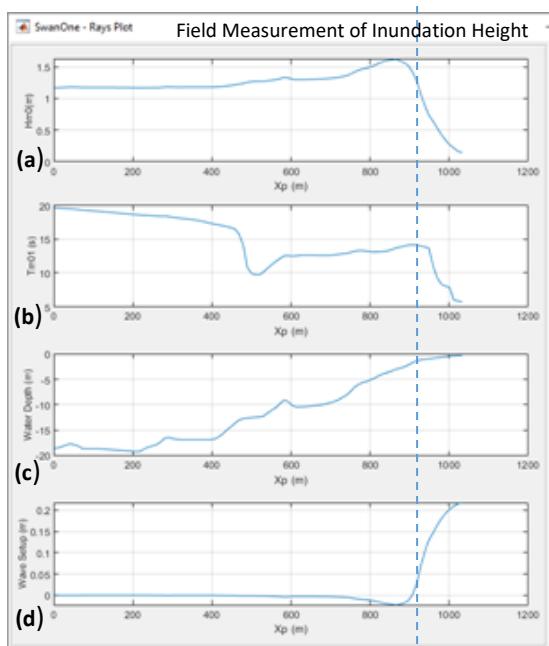


Figure 6. Results of Scenario 2, (a) Wave Height, (b) Wave Period, (c) Water Depth, (d) Wave Setup

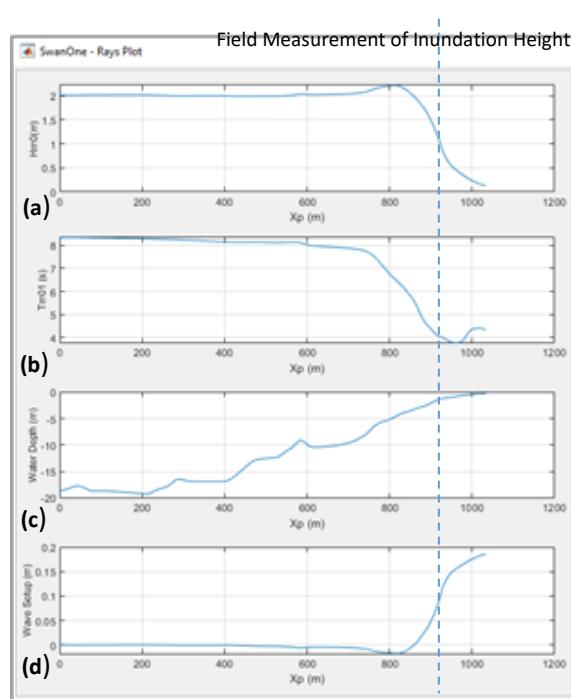


Figure 8. Results of Scenario 4, (a) Wave Height, (b) Wave Period, (c) Water Depth, (d) Wave Setup

The results of all scenarios, see in **Figure 5**, **Figure 6**, **Figure 7**, and **Figure 8**, have been shown in the graphs, consisting of wave height, wave period, water depth, and wave setup plots. Wave heights have a relatively significant difference compare to the measurement data for each scenario; they are arguably sensitive to the input parameters. The modelled water (wave) depths are similar for all scenarios. Other parameters are shown in **Table 2**, and inundation heights are interpreted as,

$$H_i = H_{mo} + \text{Water Depth} + \text{Wave Setup} \quad (9)$$

Table 2. Wave modelling results from all scenarios

Parameter/Scenario	Scen. 1	Scen. 2	Scen. 3	Scen. 4
Wave Height (H_{mo})	0.218 m	1.2 m	1.533 m	1.12 m
Water Depth	1.2874 m	1.314 m	1.658 m	1.373 m
Wave Setup	-0.000449 m	0.02658 m	0.215 m	0.086 m
Wave Period (T_{mo1})	13.903 s	14.13 s	12.228 s	4.055 s
Inundation Height from Wave Modelling (H_i)	1.569 m	2.538 m	3.406 m	2.58 m
Error (to the measurement data)	53.58%	24.91%	0.77%	23.67%

Scen.: scenario

The best and chosen result is wave inundation height close to field measurement data, scenario 3. The inundation height of this scenario on the land reaches 3.4 m (error 0.769%). This wave height is noticeably too high to mitigate with hard structures measures, such as building breakwater or tsunami barrier. Therefore, soft measures through a comprehensive mitigation plan based on local community preparedness are relevant.

Tsunami Perspective Study

The tsunami perspective study was carried out through a questionnaire survey for the 2018 Sunda Strait Tsunami victims. The questionnaire was designed to obtain various essential information to determine the awareness and preparedness of residents in Legundi island, including demographics of victims, sources of tsunami knowledge, evacuation behaviour, and post-disaster.

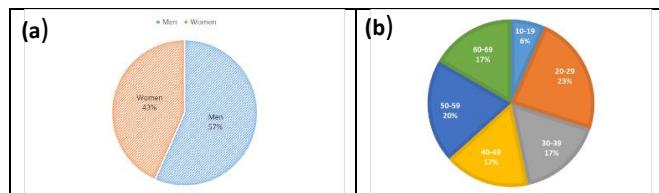


Figure 9. (a) Respondent gender (b) Respondent ages

Thirty respondents gathered during the survey, and this was considered representative enough to describe the overall population (200 households) who experienced the tsunami on the island. Demographics of respondents consisted of 57% men and 43% women, and age distribution was evenly distributed for adolescents, youth, adults, and the elderly, as shown in **Figure 9**.

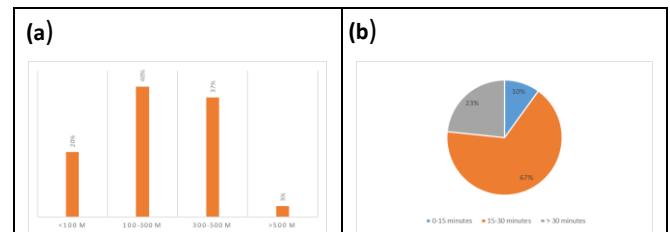


Figure 10. (a) Respondent house's distance from the shore (b) Respondent evacuation time during the tsunami

Most people in Legundi island live close to the shore, namely less than 500 m from the coastal line, see in **Figure 10a**. People are indeed very aware of reaching the higher ground to save a life during the tsunami. Based on the responses, people on the island need at least 15 minutes to get to a safer place (see **Figure 10b**). Considering the tsunami's travel time (30 minutes), this island is deemed sufficient for people to reach the protected points and evacuate themselves.

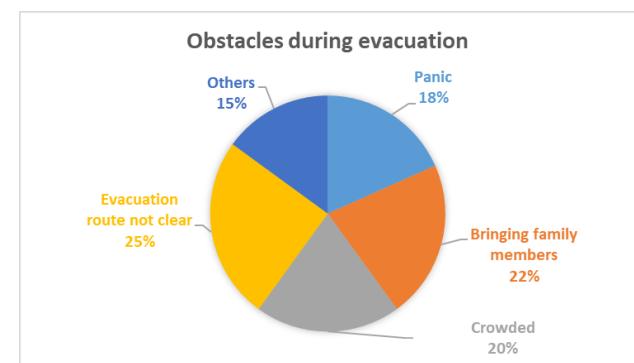


Figure 11. Respondent evacuation's obstacles

However, 25% of the residents feel the most challenging obstacle during evacuation is the confusing evacuation route, see in **Figure 11**. We observed that the evacuation signs did not exist on this island, and the evacuation route was considerably inefficient (too long to the direction of the higher ground). Moreover, the available evacuation time (30 minutes) will work well to save people if only an early warning system exists on the island, which is not the case.

Conclusions

The tsunami wave modelling in Legundi island was conducted. Scenario 3 is proposed to the best-fitted compared to the field measurement from prior research, which was 3.38 m of inundation height. In this modelling, inundation height (3.4 m) was the combination of wave height (1.533m), water depth (1.658m), and wave setup (0.215m; which leads to an error of less than 1 %. The tsunami travel time is estimated at around 30 minutes which in turn to be available evacuation time.

Based on the tsunami perspective study, a resident is not prepared enough to face extreme waves like a tsunami. Installing a tsunami early warning system to benefit available evacuation time and providing regular tsunami drilling programs for locals is a must on this island.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Authors wishing to acknowledge the research are financially supported by the SIMLITABMAS RISTEK-BRIN 2019-2020 program, supporting the research financially.

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