Tsunami Wave Transformation in Selesung Bay (Lampung)

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Abstract. The 2018 Sunda Strait tsunami is categorized as a volcano tsunami that happens due to Mount Anak Krakatau's flank collapse. The modeling effort with this kind of tsunami is challenging. Selesung bay is located in Legundi Island, one of the suffered islands from the tsunami in the Krakatoa water area. This research tries to do a local scale simulation of the bay's tsunami waves using shallow water wave simulation software. The model permits wave transformation simulation in the bay from the offshore side to the coastal point. The result presents that the inundation height of the tsunami in Selesung bay is a combination of wave height (1.5 m), water depth (1.65 m), and wave set-up (0.2 m). Those properties are summing up 3.4 m modeled inundation height, which is committing to less than 1% error from the measured data of 3.38 m. The model also gives an insight into the diffracted wave condition in Selesung bay with a wave height of 2.8 m and a wave period of up to 25 s. All in all, the model shows a good agreement with measured data and permits the benchmarking points for further study.

1. Introduction
The 2018 Sunda Strait tsunami has been confirmed due to a flank collapse of Mount Anak Krakatoa ([1] and [2]). Although the tectonic phenomenon drove most tsunami events, the volcano tsunami (like in the 2018 Sunda Strait) is categorized special issue. Typical tsunami wavelength and period generated by a volcanic landslide are shorter and account for less than 10 minutes or even less than 5 minutes ([1], [3] and [4]).

[1], [5] and [6] mapped the damaged areas along the coast of Java and Sumatra due to the waves (see Figure 1). Those areas consisted of populated inhabitants such as Tanjung Lesung, Carita, and Kalianda; Less populated, such as Cipenyu and Kiluan; islands between Krakatau complex and the mainland, such as Sebesi and Legundi island. In the latter case, [7] conducted a questionnaire and social surveys to analyze community preparedness against a tsunami. They also noticed that 2 of 6 sub-villages (Selesung 1 and 2) suffered from the 2018 tsunami, 200 households. Although only one person died, this disaster was traumatic for the community since the first-time tsunami reached this island in modern history.
Some researchers attempted to do global-scale models and produced a good agreement with available data, such as from [2], [3], and [4]. For the case of Legundi island, the tsunami wave diffracted to enter the funnel-shaped Selesung bay. As in nearshore wave, shoaling and refraction dominantly determine the wave propagation parameters. [1] measured 3.38 inundation height in the Selesung bay with a run-up distance reach 200 m from the coastline. This study focuses on the local scale modeling of tsunami transformation to elaborate on the wave’s components entering Selesung bay (Legundi island).

2. Methodology
This research is modeling the tsunami as a wave transformation in a nearshore zone based on the 2018 Sunda Strait tsunami in Legundi island. One of the main components in the modeling completion is having the precision bathymetric data. A bathymetric field survey is done in Selesung bay (Legundi) by using bathymetric survey equipment. Since it is 1D modeling, a representative transect of the bathymetry contour is chosen to be one of the model's inputs.
Some scenarios are developed to obtain the possible condition of the 2018 Sunda Strait tsunami in Selesung bay. The field measurement data of [1] is used as a validation of the scenarios. The complete flowchart of the research methodology is shown in Figure 2.
3. Bathymetric Survey
A bathymetric survey was conducted in Selesung Bay on August 9, 2020. The survey applied Garmin GPSMAP 585 Plus on a 5 GT boat with 10 m length, 2.6 m width, and 1.16 draft. The boat speed is maintained at less than 8 knots/hour as limited by the equipment applicability. The survey lanes were followed by the boat, which was designed to have 6 main and 2 cross lanes (Figure 3a). The sounding result was interpolated to produce the contour map and calibrated with related tides data from [8]. Figure 3b was the final result of the bathymetric survey map. The map shows the model's offshore boundary has -18.60 m depth (although the deepest point is -19.30 m depth) and is located 882 m from the land boundary. The contour depth is gradually lesser to the nearshore zone, reaching 0 m on land.
4. Nearshore Wave Transformation

The wave is transforming when entering shallow water or when it starts to touch the bottom. For a water channel without obstacles (structures) in the bay, shoaling and refraction exist [9]. Those two processes change the wave height and direction along the bay respectively. A harmonic wave, propagating over a fixed bathymetry with a gentle slope and no currents, the dispersion relationship remains valid as follow,

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

In which,

$$\omega = \frac{2\pi}{T} \quad k = \frac{2\pi}{L}$$

Rearrangement of the above equations will result in the wave phase speed and group velocity as a function of depth as follows,

$$c = \sqrt{\frac{g}{k} \tanh(kd)} \quad (2)$$

$$c_g = nc \quad \text{with} \quad n = \frac{1}{2} \left(1 + \frac{2kd}{\sinh(2kd)}\right) \quad (3)$$

Such variations in the group velocity cause variations in local wave energy and hence amplitude (half of the wave height) along the bay, called shoaling. For parallel contour bottoms and under stationary conditions, the energy conservation for shoaling only preserves as follow,

$$P_2b = P_1b \rightarrow [Ec_g]_2 = [Ec_g]_1 \rightarrow \frac{1}{2} \rho g a^2 c_{g,2} = \frac{1}{2} \rho g a^2 c_{g,1} \quad (4)$$

So,
Suppose an oblique harmonic wave approaches the straight coast. In that case, the wave will slowly change direction due to the depth variation along the wave crest with a corresponding variation in phase speed, called refraction. For a situation with parallel depth contour, Snell's law preserves as follow,

$$\frac{d}{dn}\left(\frac{\sin \theta}{c}\right) = 0 \text{ or } \frac{\sin \theta}{c} = \text{constant}$$

Hence, the conservation of energy of the wave ray taking into account shoaling and refraction as follow,

$$P_2b = P_1b \rightarrow [Ec_g]_2 = [Ec_g]_1 \rightarrow \frac{1}{2} \rho g a_2^2 c_g = \frac{1}{2} \rho g a_1^2 c_{g1}$$

In the model, the one-dimensional energy balance equation is carried out as follow,

$$\frac{\partial c_{g,x}}{\partial x} E(\omega, \theta; x, y, t) + \frac{\partial c_{\theta x}}{\partial \theta} E(\omega, \theta; x, y, t) = S(\omega, \theta; x, y, t)$$

The first term represents the propagation of energy in space ($c_{g,x}$), thus accounting for the shoaling process. The second term represents depth-induced refraction ($c_{\theta \theta}$ in $\theta$). Lastly, the right-hand side term is the source term of energy density, representing the effects of wave generation, nonlinear wave-wave interactions, and dissipation [10].

The computation of wave-induced set-up is based on a vertically integrated momentum balance equation, which represents a balance between the wave-induced force (radiation stress gradient normal to the coast, $S_{xx}$) and the vertically integrated hydrodynamic pressure gradient.

$$\frac{d\eta}{dx} = -\frac{1}{\rho g (d+\eta)} \frac{dS_{xx}}{dx}$$

5. Results

Some scenarios are developed related to the model's initial and boundary conditions to describe the field measurement data of tsunami wave height. The transformed wave period and wave height of the input spectrums observe to be the most sensitive parameters that influence the model's result. Table 1 presents four scenarios generated in this study to be chosen the most reliable for the 2018 Sunda Strait tsunami modeling in Selesung bay.

| Parameter/Scenario         | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|----------------------------|------------|------------|------------|------------|
| 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     |
| Transformed wave height ($H_{mo}$) | 1 m        | 3 m        | 3 m        | 2 m        |
| Transformed wave period (T) | 300 s (5 min.) | 50 s      | 30 s       | 10 s       |

[1] estimated (based on the same events and resident interviews), the wave period was less than 5 minutes, used for the first (test) scenario model. The second to fourth scenarios are chosen based on the model's sensitivity to produce the measured value. The dashed lines in figures 4 and 5 indicate the
measurement point of surveyed tsunami wave height (3.38 inundation height) and are located 922 m from the offshore boundary.

Scenario 1 (Figure 4a) presents an odd shape and value of wave transformation in the nearshore; this is arguably caused by the relatively long period compared to the bay dimension. Scenario 2 (Figure 4b) has formed quite a nice wave transformation yet wrong wave height's value, again due to arguably the wave is way too long. Scenario 3 (Figure 4c) produced quite a good and reliable result to describe the studied case. Scenario 4 (Figure 4d) confirms the previous scenario's reliability, and the correspondence period is too short for the case study.

The best fit to the measured data is scenario 3, the detail of wave propagation to the shore and its parameters are shown in Figure 5. At the measurement point, the significant wave height (tsunami wave height) is 1.533 m, the wave set-up is 0.215 m, and the water depth is 1.658 m. These properties account for 3.406 m inundation height and error 0.79% from the data. Figure 5d also gives an insight into the evolution of the wave period from offshore to the coastal points in which the offshore boundary wave period is 25 s.

6. Conclusion
The numerical model delivers gradual changing of the waves when entering the Selesung bay of Legundi island. Some scenarios need to be designed to validate the modeled inland wave height with the measured evidence. The result shows that the inundation height of the tsunami in Legundi island is a combination of wave height (1.5 m), water depth (1.65 m), and wave set-up (0.2 m). These parameters sum up 3.4 m modeled inundation height, which is committing to less than 1% error from the measured data (3.38 m inundation height). The model also gives an insight into the diffracted wave condition in Selesung bay with a wave height of 2.8 m and a wave period of up to 25 s.
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