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Numerical Modelling of Volcanic Landslide Tsunami at the Anak Krakatau Island (Indonesia) – A Potential Collapse of the South-Eastern Flank

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ABSTRACT
The Krakatau Island volcano in Indonesia erupted on 22nd December 2018 which caused the collapse of the south-west flank of the Anak Krakatau Island triggering a tsunami. Any future collapse is expected to be on the south-eastern flank. Therefore, tsunami from a south-eastern flankcollapse has been numerically modelled in this study. The initial tsunami waves similar to the 22nd December 2018 event have been generated based on previous studies found in the literature search. The MIKE21 Flow Model FM of DHI has been used in this study to simulate the tsunami. Sample results from the tsunami modelling study are presented in this paper for illustration purposes. The methodology described in this paper for modelling the volcanic tsunami at Anak Krakatau Island could also be applied to simulate this type of events at other sites around the world.

Key words: Tsunami, Volcano, Natural Hazards, Anak Krakatau, Krakatau Island, Bay of Bengal, Numerical Modelling, Port Development, RHDHV

INTRODUCTION

During the 22ndDecember 2108 eruption the south-western flank of the Anak Krakatau Island collapsed due, in part, to the of higher water depth and steeper topographic slope on this segment of the island. There remain two flanks subjected to potential future collapses, namely the south-eastern and north-eastern flanks. The south-eastern flank is in deeper water and has steeper slope compared to the north-eastern flank. Therefore, there is a greater risk of the south-eastern flank collapsing in future (potentially with the generation of similar conditions as the 2018 event). Hence, tsunami from a south-eastern (135°N) flank collapse of the Anak Krakatau Island has been numerically modelled in this study.

The MIKE21 Flow Model FM of DHI [1] has been used in the present study. The initial tsunami conditions (changes in sea surface) similar to the 22nd December 2018 event were generated in the present study that matched the findings of other authors. Initially numerical modelling of the 22nd December 2018 was carried out to validate the tsunami model. Then the validated model was used to simulate the tsunami generated from the south-eastern flank of the Anak Krakatau Island in the present study. Sample results of tsunami levels and arrival time from the modelling study are presented in this paper for illustration purposes only.

The model could be used to simulate the passage of a tsunami anywhere within the Bay of Bengal and its surroundings including Indonesia. The methodology described in this paper for modelling the tsunami generated at the Anak Krakatau Island in the Sunda Strait could also be applied to simulate this type of events at other sites around the world. The flowchart in Figure 1 [adapted from (2)] illustrates the steps and the software used in the present study.

The general definition of tsunami level and wave height is illustrated in Figure 2 [3].

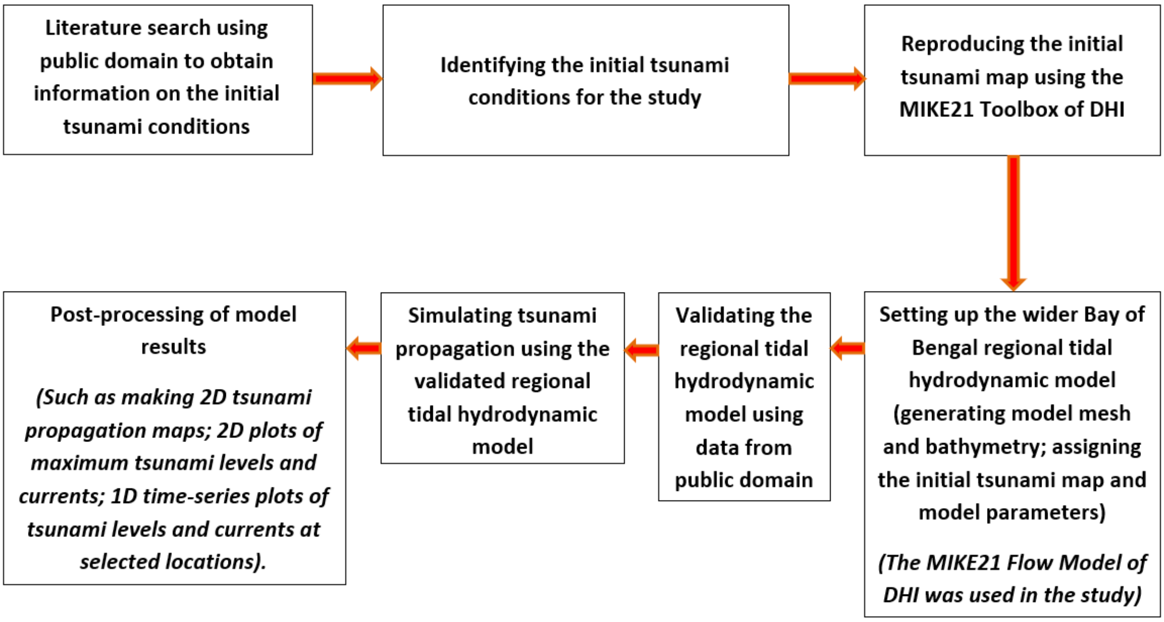


Fig. 1 Steps and software used in the tsunami modelling study [adapted from (2)]

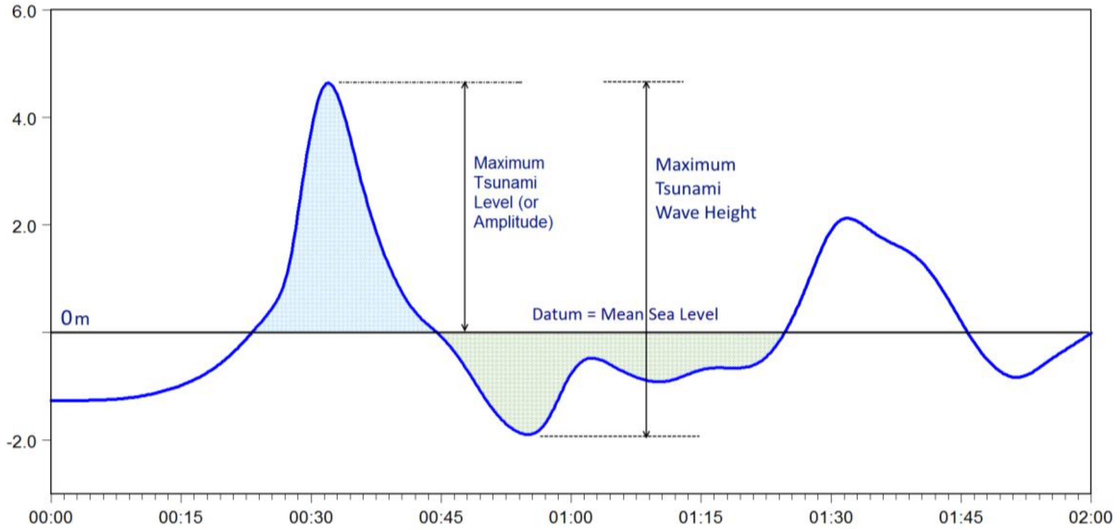


Fig. 2 General definition of tsunami level and tsunami wave height [3]

Regional Tidal ModelSet Up by Royal HaskoningDHV

Royal HaskoningDHV (RHDHV) has set up a two-dimensional Regional Tidal Hydrodynamic Model for the Bay of Bengal and its surroundings using the MIKE21 Flow Model FM software of DHI [1].

The regional model covers the coastlines of six countries – India, Sri Lanka, Bangladesh, Myanmar, Malaysia and Indonesia (see Figure 3). The model bathymetry (as shown in Figure 3) was obtained from the C-Map Global Database [4]. This regional tidal model was used in the study to simulate the tsunami propagation.

Model Mesh and Bathymetry

A flexible (triangular) mesh was used with variable mesh size distribution to obtain accuracy in the model results. Attention was given to the shallow areas and inside the SundaStrait particularly around the Krakatau Island.

Typically, 20-30 grids (ideally 40 grids) per wavelength are required to correctly resolve the physical processes of tsunami propagation. Shallower waters have shorter wavelengths. Therefore, smaller grid sizes are required for shallower waters.

The mesh size distribution was generally as below:

- 50m grid size at 1m depth
- 150m grid size at 10m depth
- 500m grid size at 100m depth
- 1500m grid size at 1000m depth

- 3000m grid size for the remaining deeper areas

The bathymetry of the model domain was obtained from the C-Map Database [4]. Figure 3 shows the model domain and bathymetry.

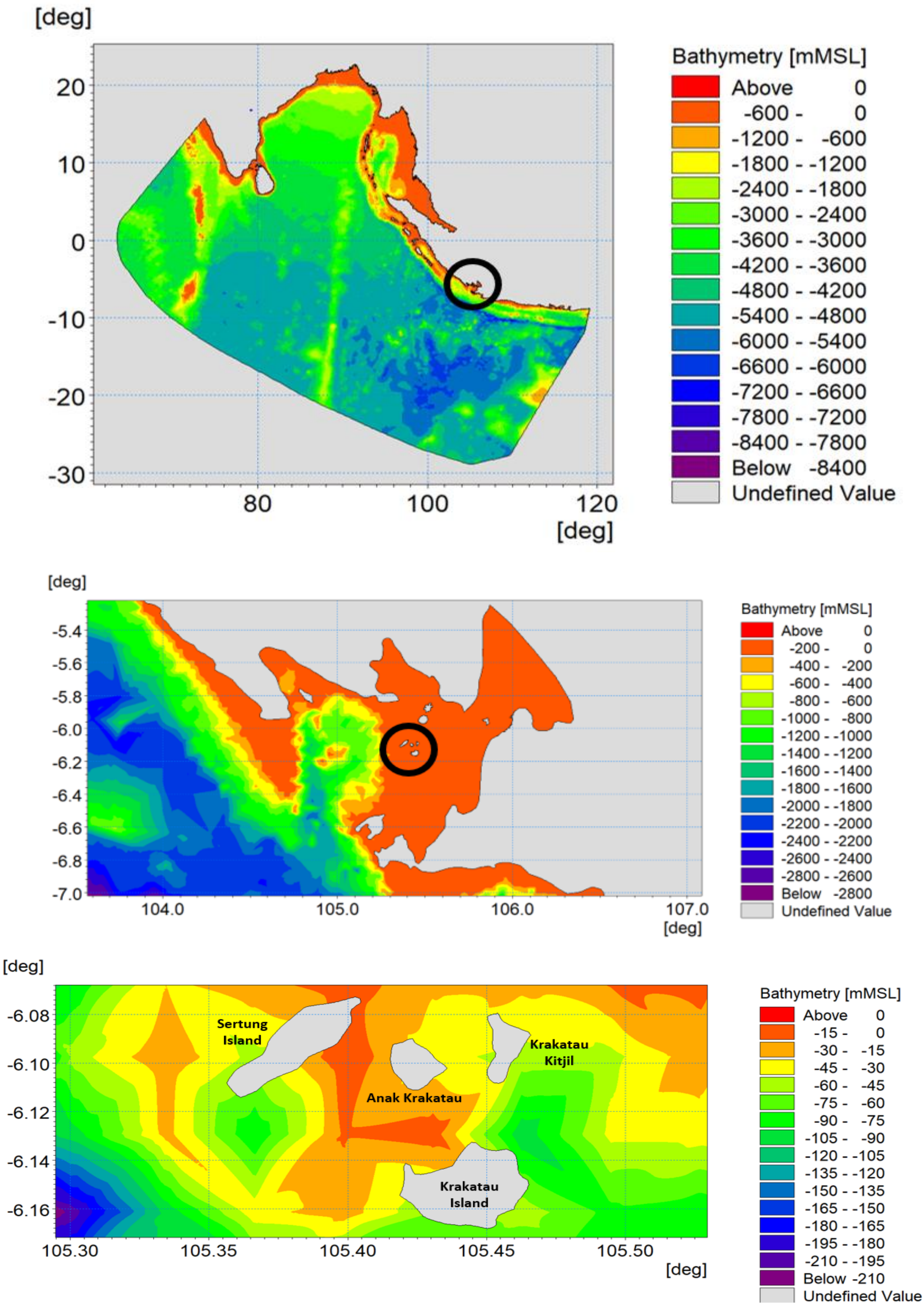


Fig. 3 The regional model domain and bathymetry [with zoomed-in views]

Model Parameters

Some other major model parameters are given below:

- Minimum time step = 0.01s
- Maximum time step = 15s
- Critical Courant-Friedrich-Lévy (CFL) number = 0.8
- Run duration = 3 hours
- Higher order numerical scheme used
- Coriolis force = varying in domain

Initial Tsunami Levels

The generation of the initial tsunami levels from the 22nd December 2018 event has been described in [5]. The parameters and approach used in [5] for the south-western slide were also used to generate the initial tsunami levels from the south-eastern flank collapse.

The initial tsunami condition used in the [5] study was at the time when the tsunami wave had developed (i.e. ~50 seconds to 1 minute after the event) for input to the hydrostatic model. The initial tsunami wave length was approximately 2.2km and the initial tsunami wave period was approximately 63s in view of the hydrostatic modelling approach used in the [5] study. The initial tsunami wave level was approximately 75m. Figure 4 shows the initial tsunami levels used in the present study from the south-eastern flank collapse of the Anak Krakatau Island.

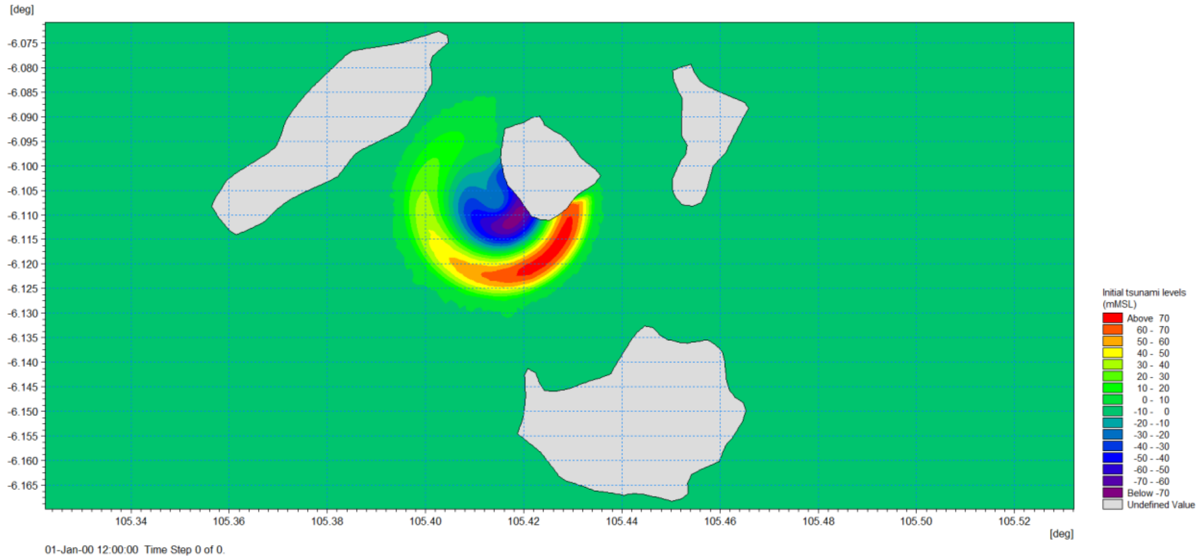


Fig. 4 Initial tsunami levels (potential south-eastern flankcollapse)

Model Calibration

The modelled peak tsunami levels and arrival time from the 22nd December 2018 event were extracted at selected locations. These locations are shown in Figure 5. Observed tsunami level at Carita during the 22nd December 2018 event was obtained from [6] as reported in [7]. Observed tsunami level and arrival time at Marina Jumbo were obtained from [8].The modelled tsunami levels and arrival time are compared inTable 1 with the observed values where available.

Table -1 Modelled and observed tsunami levels and arrival timefrom the 22nd December 2018 event

Ciwandan Port (6.016°S,105.954°E)		Marina Jumbu (6.19°S,105.82°E)		Carita (6.263°S,105.8°E)	
Modelled Tsunami	Observed Tsunami	Modelled Tsunami	Observed Tsunami	Modelled Tsunami	Observed Tsunami
0.7 to 1.6m (51 minutes)	- (50 minutes)	0.8 to 1.3m (36 minutes)	0.9m (29 minutes)	1.4-2.2m (34 minutes)	2.0m -

A good agreement was found both in the modelled and observed tsunami levels and arrival time at various locations within the Sunda Strait. Therefore, it is concluded that the present model can predict the tsunami levels and arrival timeanywhere within the model domainwith an acceptable level of confidence for the circular collapse scenario.

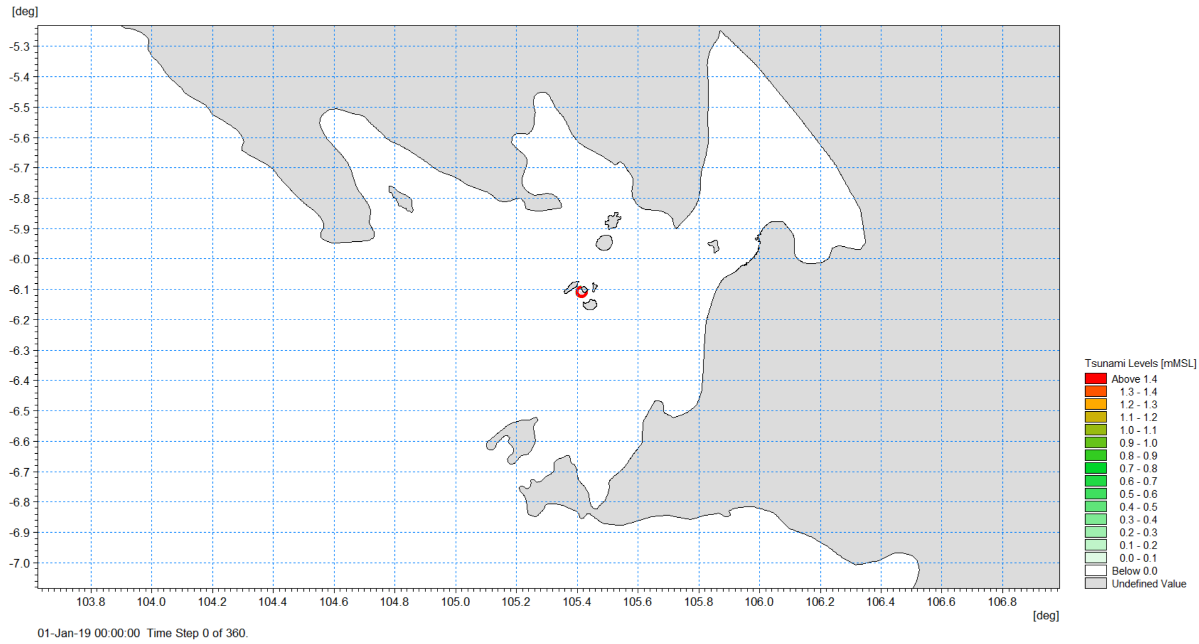
Model Results and Discussion

Propagation of tsunami waves over time is shown in Figure 6. Figure 7 shows the time-series of tsunami levels at selected locations. These locations were shown in Figure 5. Figure 8 illustrates the maximum tsunami levels during the entire passage of the tsunami. Peak tsunami levels and its arrival time are summarized in Table 2.

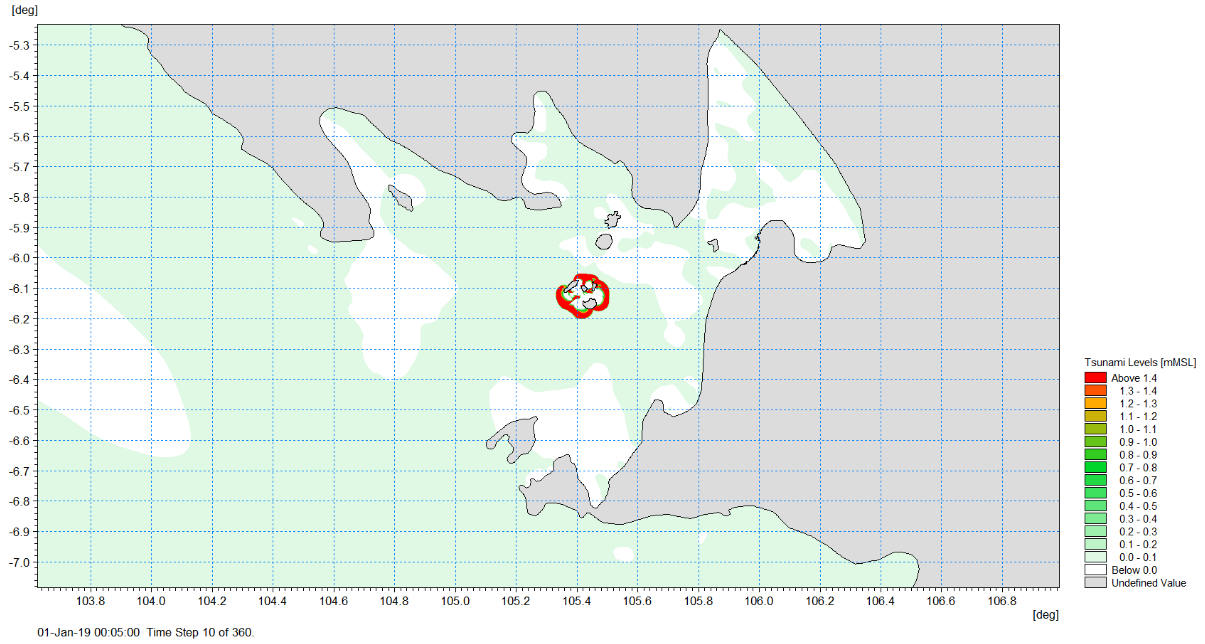
The maximum tsunami level at the Anak Krakatau Island was 68.7m. The maximum tsunami level at the Sertung Island was 29.1m. The maximum tsunami level at the Krakatau Island was 38.2m. The maximum tsunami level at the Krakatau Kitjil was 20.4m. The maximum tsunami level at Sebisi Island was 7.0m whereas the maximum tsunami level at the

Sebuku Island was 1.6m. A tsunami level of up to 3.5m was found at the Sangiang Island. A tsunami level of up to 3.0m was found at the Panaitan Island. Up to 0.5m tsunami level was found at the Sawangbalak Island. The maximum tsunami level at Legundi Island was 1.0m whereas the maximum tsunami level at the Siuntjal Island was 0.9m. The maximum tsunami levels in the Java Sea and the Indian Ocean were relatively small (0.4m and 0.2m respectively).
The model results suggest that the neighbouring islands (Sertung Island, Krakatau Kitjil Island and Krakatau Island) were quickly affected (within a few minutes) due to the proximity to the source. The Sebesi Island, Legundi Island and Siuntjal Island(all situated north of the source) were also affected relatively quickly (within 25 minutes). The Sawangbalak Island at north-east was affected within 24 minutes.The Panaitan Island at south-west was affected within 31 minutes. The Sebuku Island at north-eastwas affected within 30 minutes. The tsunami took 39minutes to reach the Sangiang Island situated north-east of the source. The tsunami took about one hour to reach the Java Sea at north-east whereas it took only about half an hour to reach the Indian Ocean at south-west.

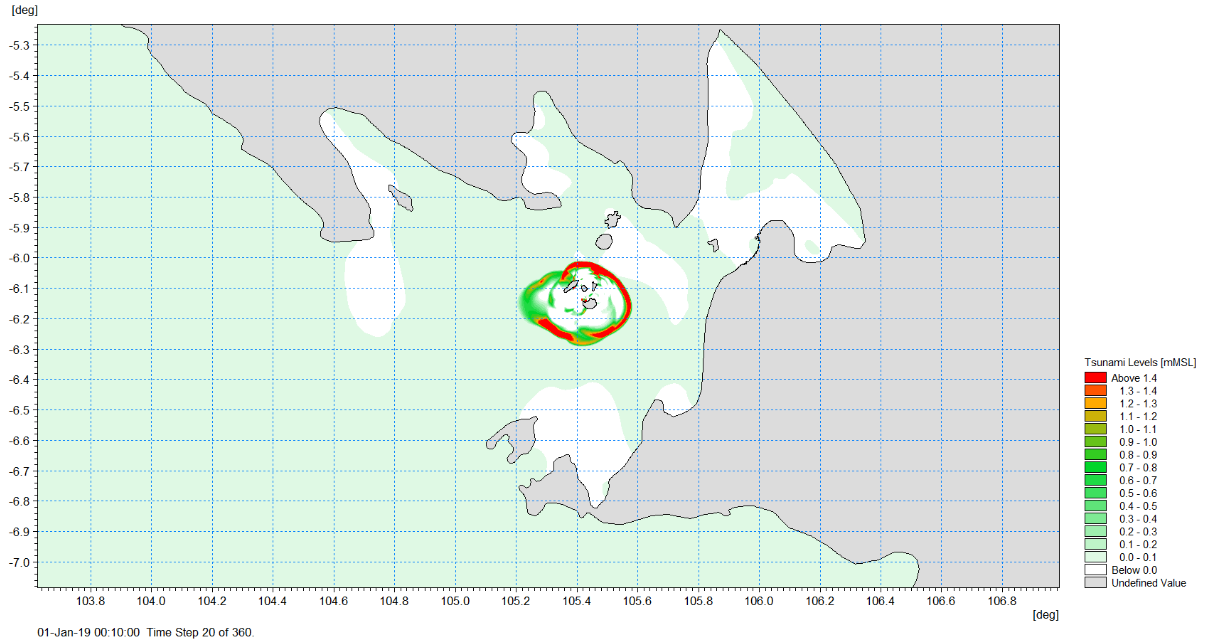
Fig. 5 Selected output locations [Image source – Google Earth]



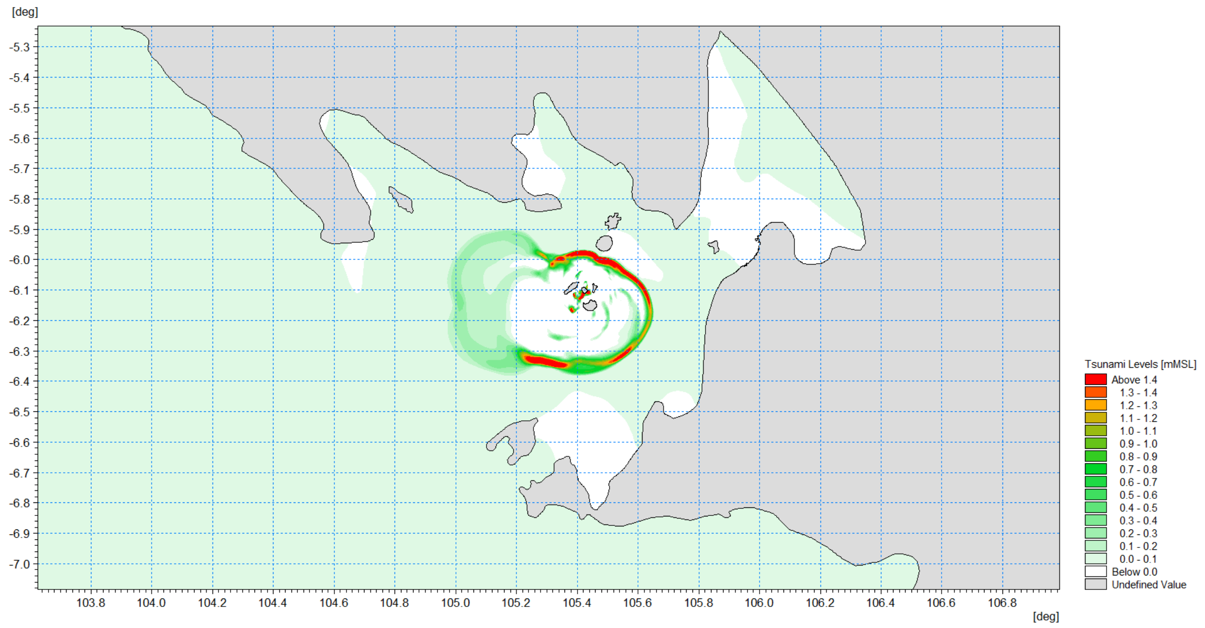
(a) Tsunami levels at t = 0 minutes



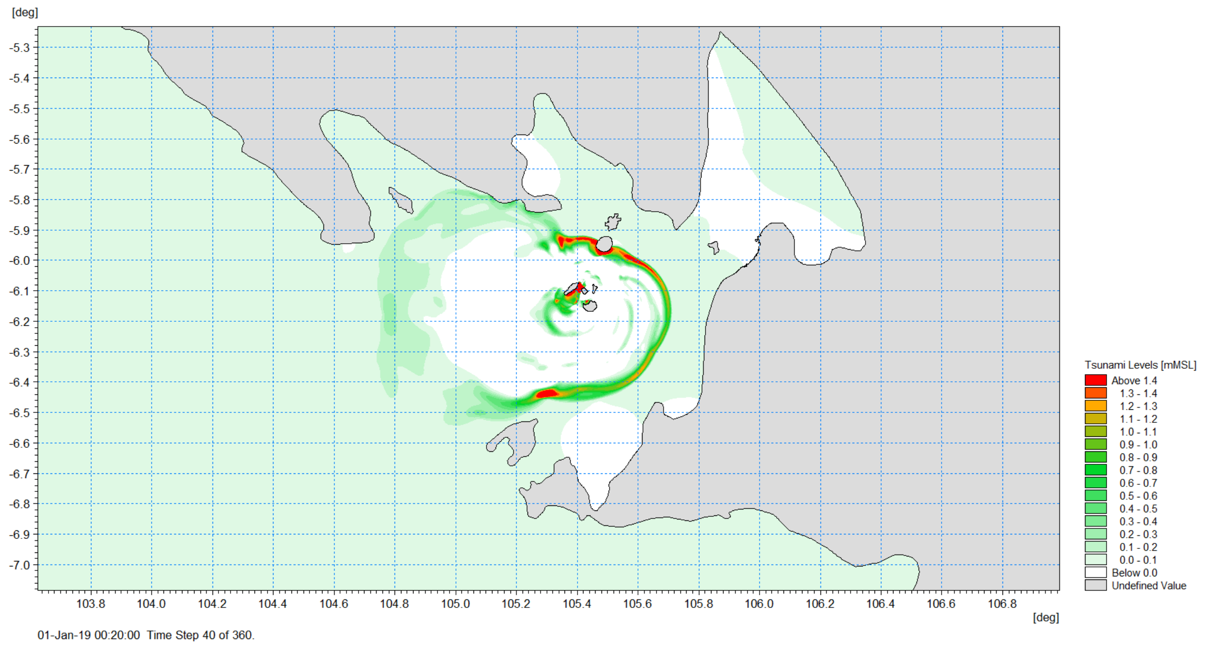
(b) Tsunami levels at t = 5 minutes



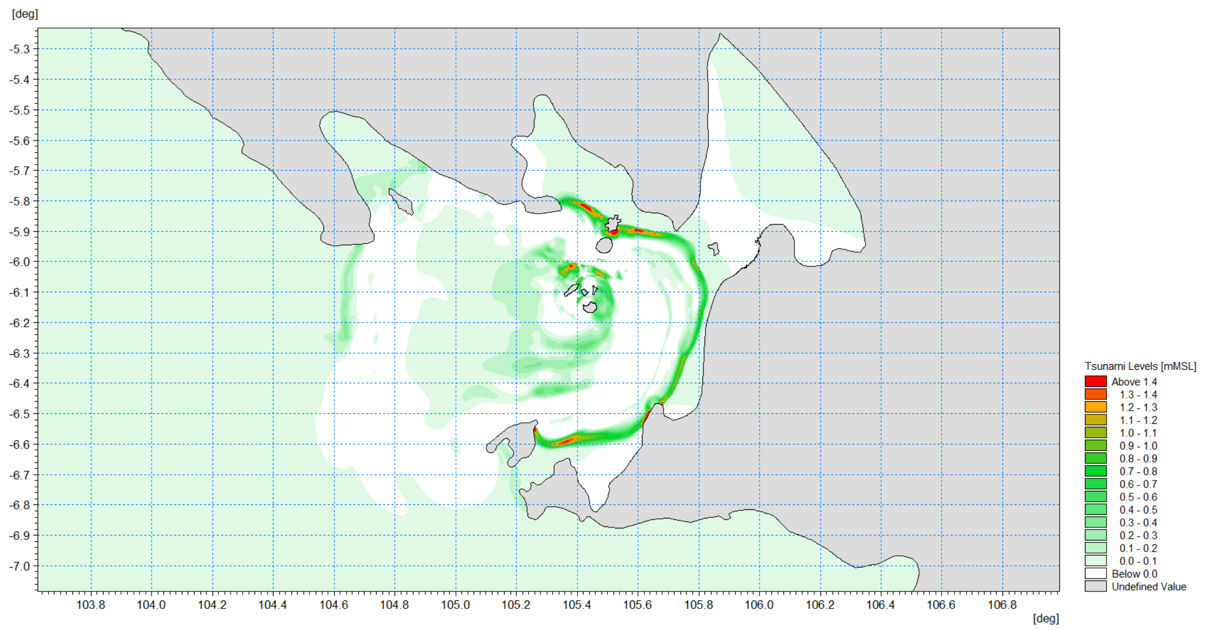
(c) Tsunami levels at t = 10minutes



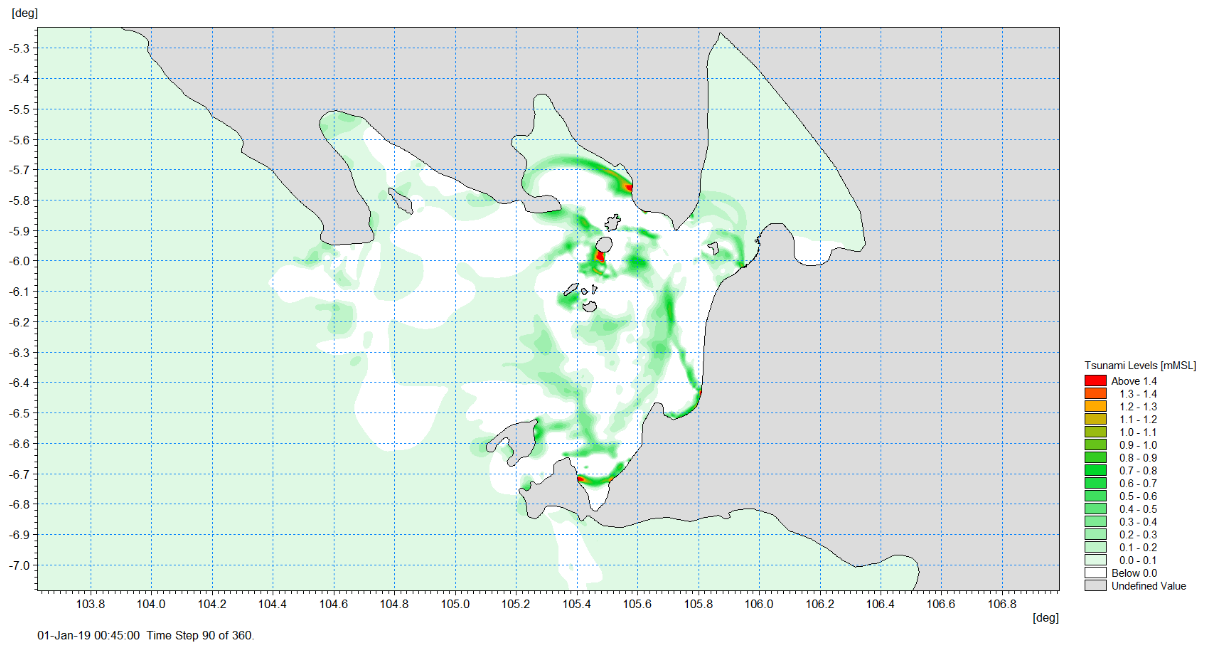
(d) Tsunami levels at t = 15 minutes



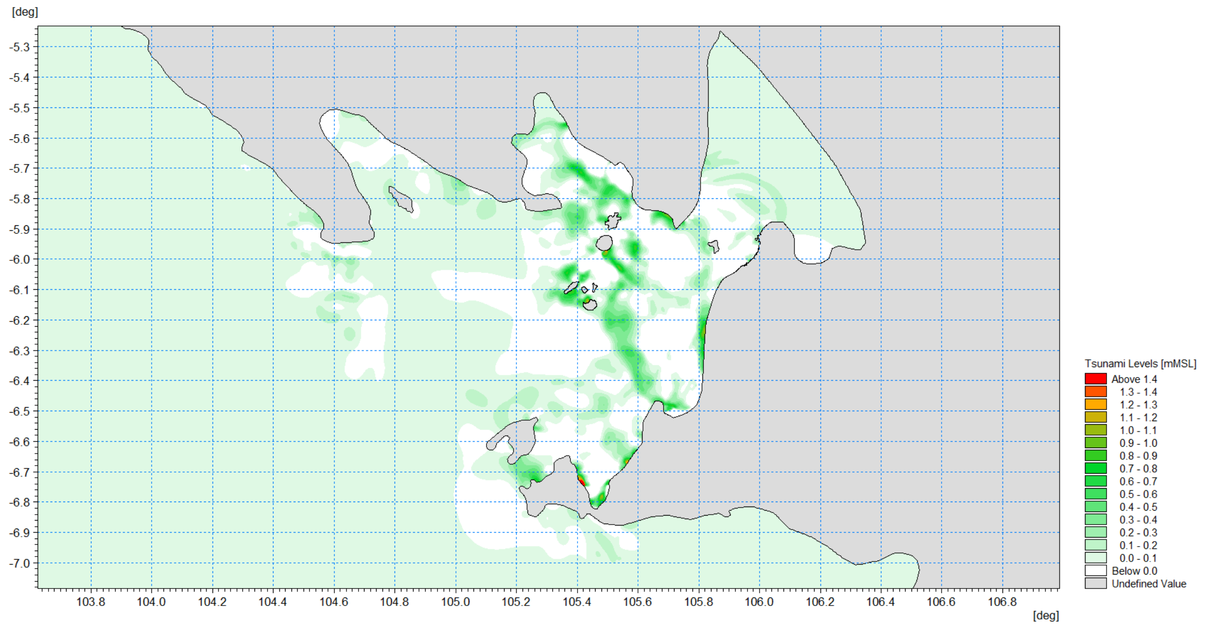
(e) Tsunami levels at t = 20 minutes



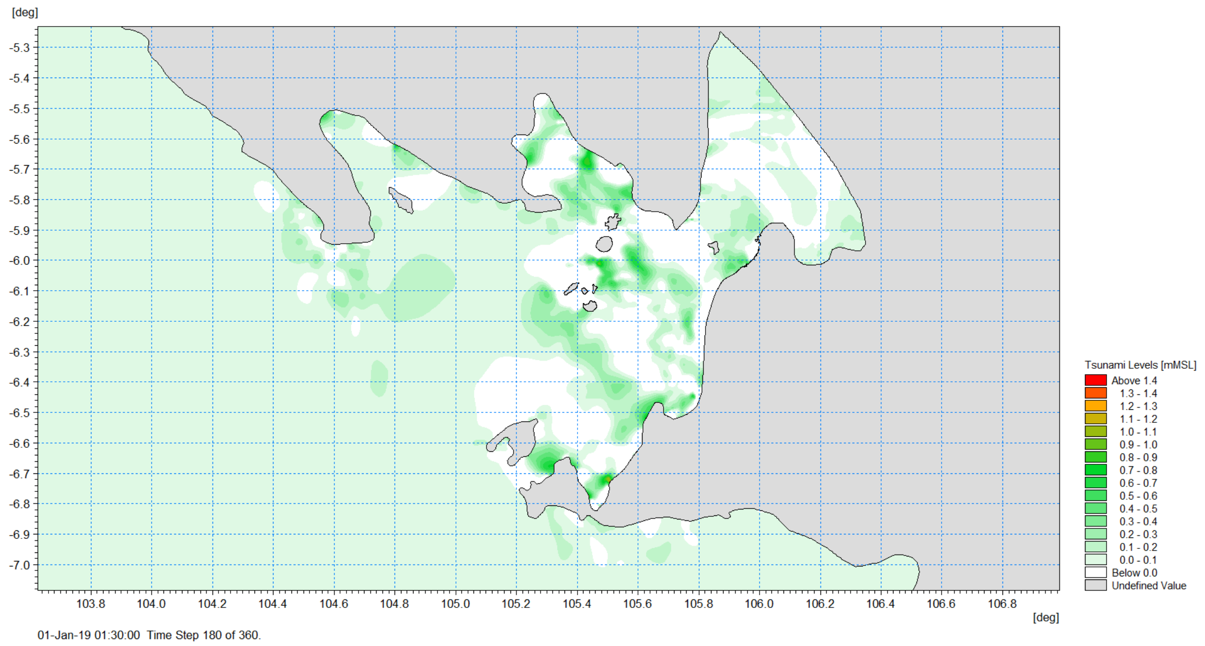
(f) Tsunami levels at t = 30 minutes



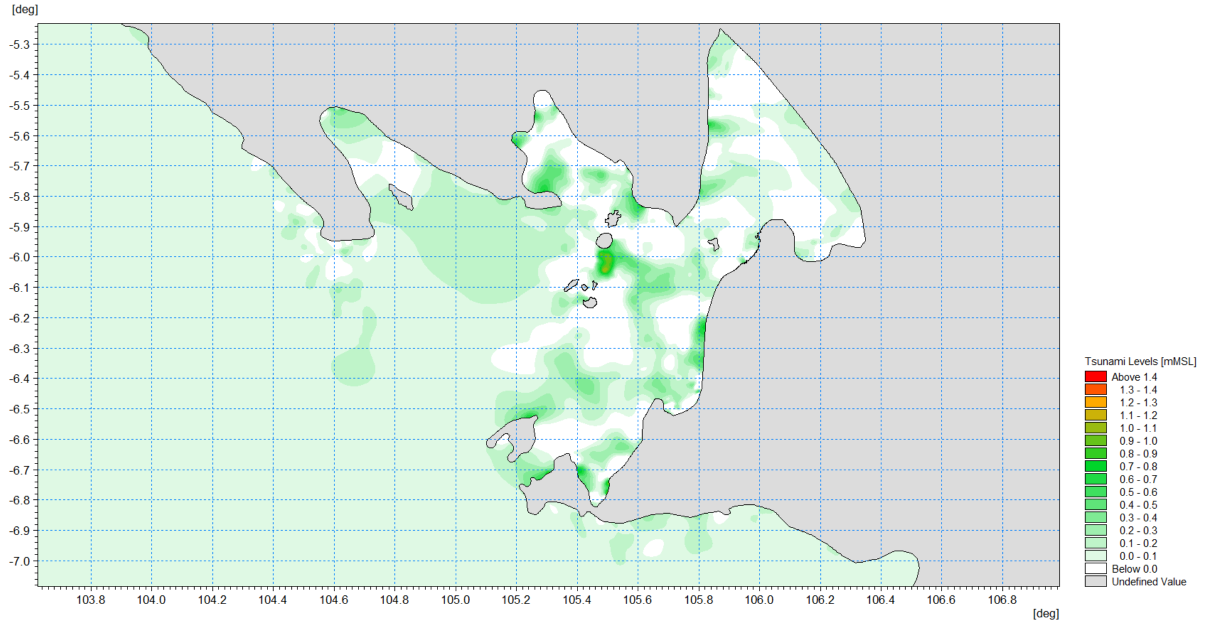
(g) Tsunami levels at t = 45 minutes



(h) Tsunami levels at t = 1 hour



(i) Tsunami levels at t = 1 hour 30 minutes



(j) Tsunami levels at t = 2 hours

Fig. 6 Propagation of tsunami waves

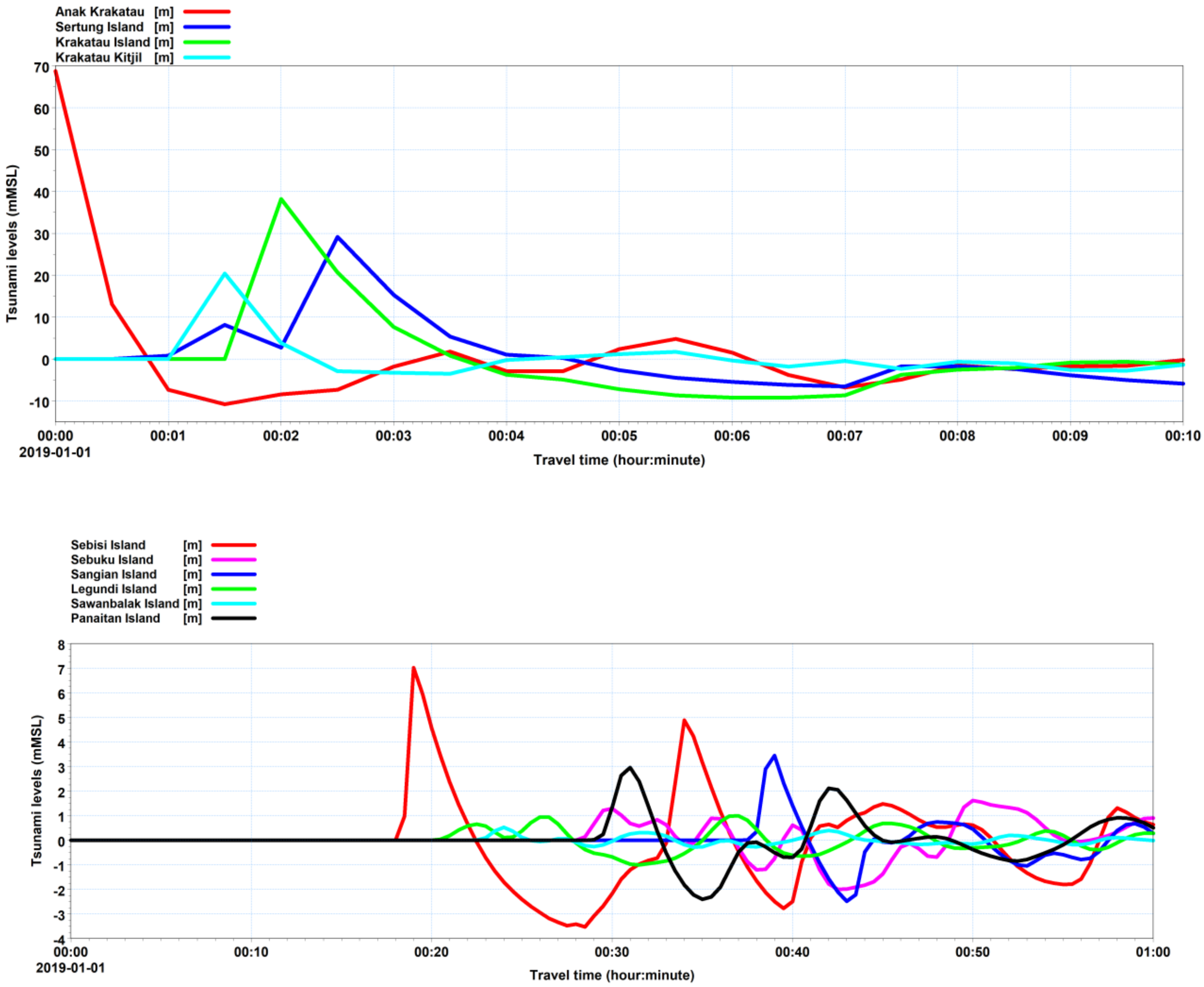


Fig. 7 Time-series of tsunami levels at selected locations

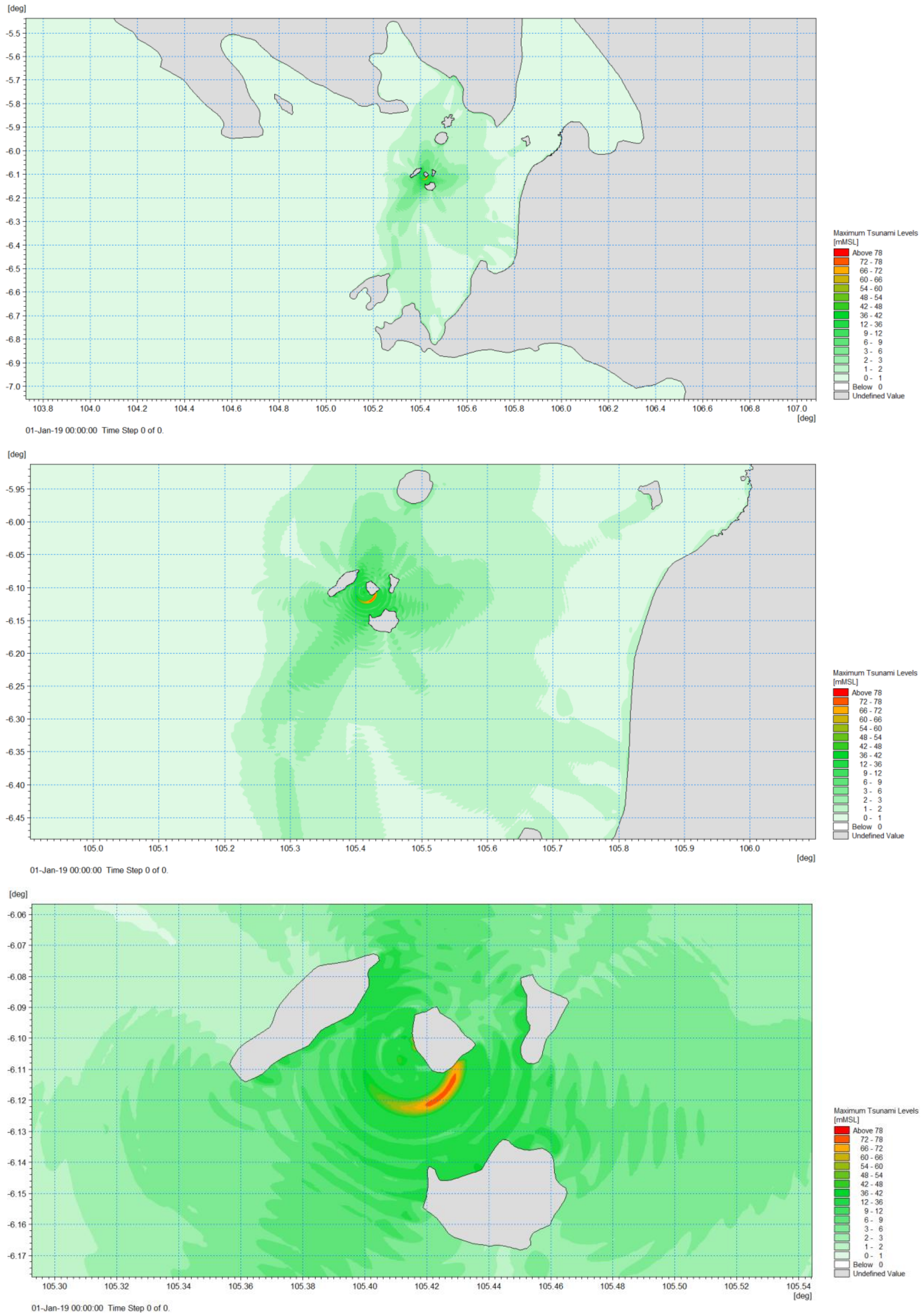


Fig. 8 Maximum tsunami levels (with zoomed-in views)

Table -2 Peak tsunami levelsand its arrival time at selected locations

Locations	Position with respect to the source	Peak tsunami levels (+mMSL)	Arrival time of peak tsunami levels (minutes)
Anak Krakatau Island	Source	68.7	0
Sertung Island	West	29.1	2.5
Krakatau Island	South-east	38.2	2
Krakatau Kitjil Island	East	20.4	1.5
Sebesi Island	North-east	7.0	19
Sebuku Island	North-east	1.6	30
Sangiang Island	North-east	3.5	39
Legundi Island	North-west	1.0	22
Sawangbalak Island	North-west	0.5	24
Panaitan Island	South-west	3.0	31
Siuntjal Island	North-west	0.9	22
Java Sea	North-east	0.4	59
Indian Ocean	South-west	0.2	28

The model correctly reproduced the tsunami phenomena observed on site with the sea level rising and receding leaving a drying beach and foreshore followed by a rapid rise in the level of the sea. The nearby islands, headlands and coastlines were worst affected due to its proximity. The highest level of 68.7m was found at south-west coast of Anak Krakatau Island immediately after the event.

A relatively higher rise in sea surface elevation was found in the shallower water depths. Rise in water level at shallow waters is higher than that in deeper waters as expected due to shoaling effects.

SUMMARY

Numerical modelling of tsunami generated by potential futuresouth-eastern flank collapse of the Anak Krakatau Island was carried out in this study. This paper illustrates how a tidal hydrodynamic modelcan be used to simulate the impacts of a tsunami on coastal developments, facilities and communities.

The methodology described in this paper for numerical modelling of tsunami generated by potential future south-eastern flank collapse of the Anak Krakatau Island in the Sunda Strait of Indonesia could also be applied to simulate this type of events at other sites around the world.

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